# NUCLEAR POWER EXPERT PANEL

## REPORT ON NUCLEAR POWER AND ALBERTA

February 2009

Dr. Harvie Andre, Chair
Nuclear Power Expert Panel
Suite 1000, 717 - 7th Avenue S.W.
Calgary AB T2P 0Z3

February 2, 2009

Honourable Mel Knight
Minister of Energy
Alberta Department of Energy
North Petroleum Plaza
7th Floor, 9945 - 108 St.
Edmonton AB T5K 2G6

Dear Minister Knight:

On behalf of the Nuclear Power Expert Panel, I am pleased to present this report which responds to the request you made to the Panel at its creation by Ministerial Order 31/2008, dated May 5, 2008.

It has been a distinct pleasure working with my fellow panelists, Dr. Joseph Doucet, Dr. John Luxat and Dr. Harrie Vredenburg. They have been generous with their time and their knowledge. The expertise of these highly qualified academics assures that this report is both accurate and complete.

I am confident that my fellow panelists share my view that this has been an interesting and personally rewarding project. We hope that it will be a useful contribution to the discussion and understanding of the issues associated with possible nuclear power generation in Alberta.

Thank you for the opportunity to participate in this interesting project.

Yours sincerely,

Harvie Andre

# NUCLEAR POWER AND ALBERTA: BACKGROUND REPORT

*Prepared for the Minister of Energy by the Nuclear Power Expert Panel*

# Executive summary

On May 8, 2008, the Minister of Energy of the Government of Alberta, the Honourable Mel Knight, issued a Ministerial Order establishing the Nuclear Power Expert Panel. The order directed the panel to "prepare a balanced and objective Report for the Government of Alberta on the factual issues pertinent to the use of nuclear power to supply electricity in Alberta." This report is the panel's response to that request.

Energy in all its forms, including electricity, is key to the maintenance and growth of all modern economies. Canada, more than most, depends on reliable, economic forms of energy for its quality of life and standard of living. This is especially true in Alberta given the significance of the production of hydrocarbon energy supplies to Alberta's economic prosperity.

Nuclear energy is increasingly being considered within public policy discussions of various energy alternatives. If any application for a nuclear power generation facility was made in Alberta, it would create significant public debate. Such discussion would be most productive if it were conducted with a clear understanding of the nature of nuclear power generation and its relative risks/benefits compared with alternatives. This report is based on current scientific information to help provide such an understanding.

This report does not make any recommendation regarding the advisability of constructing a nuclear power generating facility in Alberta. The panel was not asked to make any such recommendation. Key conclusions from the panel's research include:

1. Alberta's economy and population will continue to grow and significant additional electrical power will be needed to maintain and improve the standard of living of Albertans. Options include more fossil-fuel-burning power plants (with or without carbon capture), more renewable sources and greater energy efficiency, as well as nuclear power.
2. Each technology has trade-offs associated with it. Such trade-offs include the availability of technology, environmental impacts, costs and operating implications for the Alberta system.
3. The decision to build a plant – whether powered by thermal combustion, or wind or nuclear – is a private-sector decision taken by a company based on its assessment of the project's economic viability. But, as with any large industrial construction project, all such plants must obtain approval from relevant government and regulatory authorities regarding their impacts or consequences.

4. Nuclear power has been in use for generating electricity for more than 50 years, and more than 400 units are in operation worldwide. New designs, based on learning from previous incidents and from long-term safe operation, are safer, more efficient and easier to control and operate.
5. Nuclear power does not release carbon dioxide. This is a significant difference (in environmental terms) between it and traditional technologies using coal and natural gas.
6. The offsetting concerns relate primarily to nuclear waste disposal. While the spent fuel removed from a reactor is radioactive, more than 99% of this material is made up of the heavy metals uranium and plutonium, which can be recycled to be reused as nuclear fuel. The remaining waste fission products decay comparatively quickly. Thus a program of separating the spent fuel and recycling heavy metals will dramatically reduce the amount of waste to be dealt with and the time period during which this material would be radioactive at levels above the natural background radiation. (Capturing carbon from fossil fuel plants also creates storage issues.)
7. In Canada, the Federal Government has the authority and responsibility for approving and regulating all nuclear facilities and nuclear-related activities. Normal provincial approvals required for any major project would also be required, based on the Province's constitutional responsibility for land and resources.
8. Any nuclear generating project would be a major construction project and have social impacts in areas such as schools, hospitals, transportation infrastructure, Aboriginal communities, local economies, housing and so on. Significant though these issues might be, they are regularly dealt with by the Government of Alberta and its agencies and affected municipalities.

This report is written so that interested readers can gain an understanding of the issues specifically related to adding nuclear powered plants into the province's inventory of electricity generating facilities. To the extent possible, technical jargon has been avoided while ensuring comprehensive coverage of the issues involved. A bibliography is provided so that readers so inclined can delve deeper into areas of interest.

It is the panel's hope and expectation that this report will be a helpful contribution to a public discussion on nuclear power generation based on scientific evidence and empirical findings from experiences with nuclear power generation around the world.

# Table of Contents

## LIST OF FIGURES



## LIST OF TABLES

# 1 Introduction

The world's need for energy in the form of petroleum and natural gas has provided much of the impetus for rapid growth in Alberta's economy and population. In turn, this has created a growing demand for energy in the form of electricity. Currently most of Alberta's electricity needs are met by plants that burn coal or natural gas, with modest additional amounts from other sources such as hydroelectric facilities and more recently wind power. While there is considerable interest in other non-conventional power generation means such as geothermal, bio-fuel, solar, etc., it is unlikely that these technologies will be able to satisfy all of Alberta's growing electricity needs.

This report starts with an analysis of the current electricity supply and demand situation in Alberta. This analysis indicates clearly that additional supply of electricity will be needed and considers the various alternatives available to meet this anticipated future demand.

In response to this need, a range of new power generation options can be considered, one of which is nuclear power. Although there are more than 400 nuclear plants in operation around the world and several in Eastern Canada, Alberta's citizens and government have little experience with this technology. While the Federal Government has the constitutional authority to authorize any nuclear facility in the country, there is a need for the citizens of Alberta to have a reasonable level of understanding of the issues and concerns associated with nuclear power plants.

Anticipating an application to construct a nuclear plant, the Government of Alberta has created this "Nuclear Power Expert Panel", with a mandate to provide a factual report on the issues pertinent to using nuclear power to supply electricity in Alberta. The duties and functions of the panel and the list of specific issues which the panel was asked to address are shown in Appendix A. Pointedly the panel was not asked to make any recommendation for or against a nuclear power plant.

This report is intended to be an unbiased compilation of the scientifically accepted information underpinning the issues associated with nuclear power. The information contained herein is based upon facts and data supplied by panel members and by the Alberta Research Council and the Idaho National Laboratory, who were commissioned by the panel to compile background information.

To avoid any bias and appearance of bias, the panel made the decision to decline any and all invitations to meet and/or to receive submissions from proponents or

opponents of nuclear power. Also, to make the contents of the report as accessible as possible to the majority of Albertans, it is written in plain language, as free from technical jargon as possible. Should an application for construction of a nuclear plant come forward in Alberta, the panel hopes this report will provide a foundation of facts upon which an informed discussion or debate on the issues associated with nuclear power can be conducted.

Many of the issues of concern regarding a nuclear power plant are the same as the issues that would be associated with any large power plant. All thermal power plants have common elements in the sense that each has a source of heat to produce steam, which powers turbines that turn generators to create electricity. Issues regarding transmission lines, supporting infrastructure, skilled operators, water requirements, etc. are common to all power plants of a similar size.

Creating heat through nuclear reaction as opposed to the chemical reaction of carbon based fuel and oxygen is, of course, an important difference. This report focuses upon nuclear-specific aspects of this technology. This should not be taken as discounting the importance of those issues that are relevant to large-scale power plants in general.

As requested by the Minister of Energy, the work of the panel was focused on a hypothetical, large, base-load nuclear power plant. (For purposes of the report, the panel has used an 800-MW unit.) However the panel would be remiss if it did not acknowledge that in some quarters consideration is being given to the use of nuclear reactors to generate process steam – in other words, steam that would be used for purposes other than just the generation of electricity.

For example, the recovery of bitumen from oil sands, both mined and *in situ,* consumes a considerable amount of energy, usually in the form of steam. The economic and environmental issues associated with burning natural gas or other carbon based fuels to produce the steam have led to some consideration of nuclear alternatives. While nuclear reactors for these purposes may be smaller than those for large base-load power plants, the issues related to them would be very similar. The information in this report would be applicable to the consideration of any such proposed developments.

# 2 Electricity in Alberta

## 2.1 Overview

At the heart of most questions regarding Alberta's electricity sector is the issue of supply and demand. This chapter presents an overview of the current electricity market as well as how that market is expected to evolve between now and 2024.[1]

Alberta's need for electricity has grown strongly over the past decade, and this growth is expected to continue, driven by the province's economy. While it is difficult to forecast electricity growth precisely, future needs for electricity can be correlated reliably with overall economic growth. Expansion of the energy sector in general and the oilsands in particular will greatly increase the need for energy, but all sectors of the economy are growing and demographic growth also continues to be strong.

The responsibility for responding to growth in demand, and more specifically the responsibility for building new plants, rests with the market, not government. Specific choices of technology or fuel type are also made by owners of prospective plants, not the government.

## 2.2 The structure of Alberta's electricity market

Alberta started restructuring its electricity market in 1996.[2] The most significant change is that any decision to build new generating capacity is made by a private-sector owner without a guaranteed rate of return.

However, this does not mean that regulation is not present. The decision to build a plant – whether powered by thermal combustion, or wind or nuclear – is a private-sector decision taken by a company based on its assessment of the project's economic viability. But, as with any large industrial construction project, all such plants must obtain approval from relevant government and regulatory authorities regarding their impacts or consequences (such as land-use, water-use, air emissions, zoning, etc).[3]

## 2.3 Alberta's current use of electricity

The province's overall need for electricity is characterized by two key measurements:

**Capacity:** The amount of electricity produced or consumed at any instant in time is measured in multiples of Watts (W). A 60-W light bulb draws 60 Watts from the electricity grid when it is turned on. A generating plant with capacity of 200 megawatts (MW)[4] can produce up to 200 MW at any given time. Capacity can be thought of as being like the diameter of a pipe that affects how much it can carry at any moment.

'Peak demand' refers to the largest amount of capacity being used by the whole system at one time. In 2007-08, the peak demand for the Alberta system was 9806 MW.[5] Between 2000 and 2007, peak demand increased on average by 3.7% a year.[6]

**Energy:** The volume of electricity produced or consumed during a period of time is measured in multiples of Watt-hours (W.h). A 60-W lightbulb operating for one hour will consume 60 Watt-hours. A generating plant producing at the rate of 200 MW (i.e. a capacity of 200 MW) for ten hours will produce 2,000 MW.h. 'Energy' can be thought of as similar to the volume carried through a pipe over a given period of time.

In 2007 the total energy used by the Alberta electric system was just under 52,000 gigawatt-hours (GW.h)[7]. This reflects an increase of 7.2% over the five-year period from 2002 to 2007.

Different sectors of the Alberta economy have different demands for energy. Figure 1 shows how each sector contributes to the total energy demand:

1 *The information is based in large part on the ARC/INL study (ARC/INL 2008) which itself is based predominantly on the Alberta Electricity System Operator's transmission outlook through 2024 (AESO, 2005).*

2 *For an overview of some of the history of restructuring in Alberta see Daniel, Doucet and Plourde (2007).*

3 *The regulatory approval process for construction of a nuclear plant in Canada is described in Chapter 8.*

4 *The prefix mega means one million, thus a mega-Watt is equivalent to one million Watts.*

5 *Data from Alberta Energy, 2009.*

- The industrial and commercial sectors represent the majority of demand. Electricity demand from these sectors fluctuates with the provincial GDP, reflecting underlying economic activity.

- Residential demand tracks population growth very closely and is less directly tied to economic activity (though demographic shifts are obviously a function of economic activity).

## 2.4 Generation capacity

Alberta's energy is generated from more than 280 units with a combined capacity of about 12,150 MW. Between 2000 and 2007, generation capacity expanded at an average annual rate of 3.4%[8].

Figure 2 shows that most of Alberta's installed capacity is derived from coal (50%) or natural gas (38%). Note that actual energy generated from different sources does not match capacity figures, because plants have different operating characteristics. For instance, in 2007 coal-fired power plants made up 50% of capacity but generated 62% of the province's electricity, while natural gas power plants made up 38% of capacity but accounted for only 32% of energy produced.

These statistics illustrate an important distinction between different types of plants, and how they contribute to meeting demand for power as it goes up and down throughout the day:

> *Base-load* power plants generally operate for many hours over the course of the year. They are often units with inexpensive fuel and/or less operating flexibility in terms of being turned on and off.
>
> *Peaking* units can be used on short notice to satisfy peaks in demand, often use more expensive fuel, and therefore tend to operate fewer hours.

Of course the specific details of operation vary from plant to plant and across jurisdictions, but coal plants are almost always operated as base-load plants whereas natural-gas units have traditionally been considered peaking plants.[9]

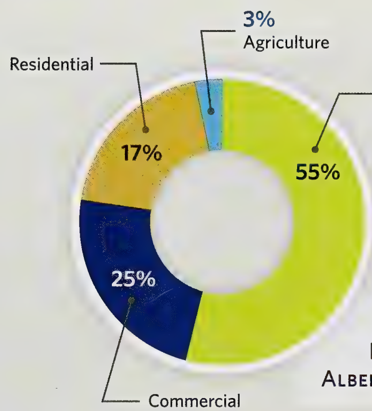



FIGURE 1
Energy use in Alberta by sector

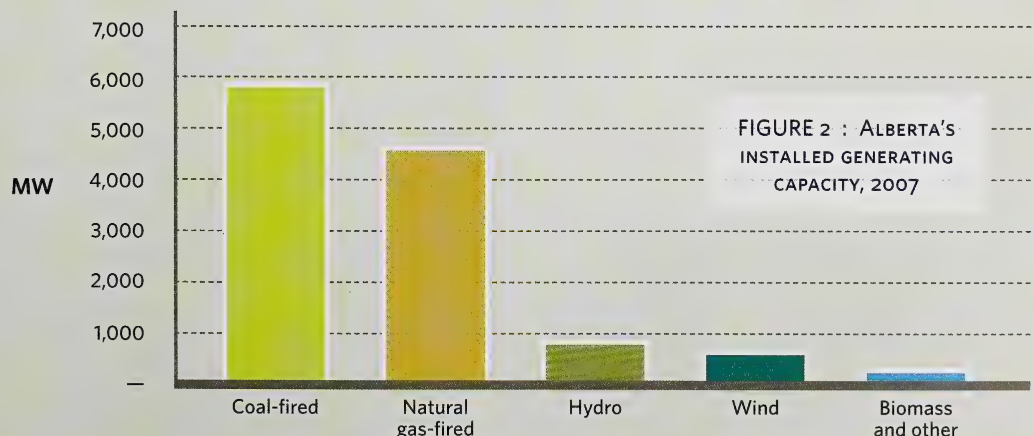



FIGURE 2 : Alberta's installed generating capacity, 2007

6 (AESO, 2005; Energy, 2008).
7 Source: Alberta Energy http://www.energy.gov.ab.ca/Electricity/682.asp . Giga means one billion.
8 Data and figures in the section come from ERCB, 2008.
9 The underlying cost and operational characteristics of different plant technologies lead to this distinction. More on this in Chapter 3.

## 2.5 Alberta's future needs for electricity

Unsurprisingly, given the growth in Alberta's economy and population, its electricity demand is growing at one of the fastest rates in North America. The most recent forecast by the Alberta Electric System Operator (AESO), carried out in 2007, indicates that by 2024, Alberta's peak demand for energy could be over 16,800 MW – a 74% increase over 2007.[10] This would reflect an increase of 3.3% a year on average.

It is difficult to forecast electricity growth precisely. However, demand for power is reliably linked to underlying economic activity, driven to a large extent by industrial expansion. Over the period 2007-2024, the AESO estimates:

- A 91% increase for the industrial sector, driven largely by growth in the oilsands. The extent of this growth depends on the cumulative production, including mined and/or thermally-extracted bitumen. The energy required in each case depends on the extraction and upgrading processes used. (See Figure 3).
- A 71% increase for the commercial sector.
- An increase in Alberta's population of 1.6% per year between now and 2020. This is the equivalent of an average addition of 25,000 residential customers per year, which would require about 53,806 GW.h more by 2024 (78% above the amount of energy consumed by this sector in 2007).

Alberta's electricity generation capacity is continuously expanding. While supply is considered adequate in the near term, an additional 3800 MW will be required by 2016 – an increase of 31% over today's capacity[11]. By 2024, the AESO projects a need for between 4600-9500 MW of capacity in addition to today's levels.

These forecasts of plant investment are prepared for planning purposes, such as transmission development. (See chapter 7 for a further discussion of transmission in Alberta.) However, as noted earlier in this chapter, details of capacity expansion (such as the timing and the type, size and location of plants) are left to the market and private investor-owned companies.

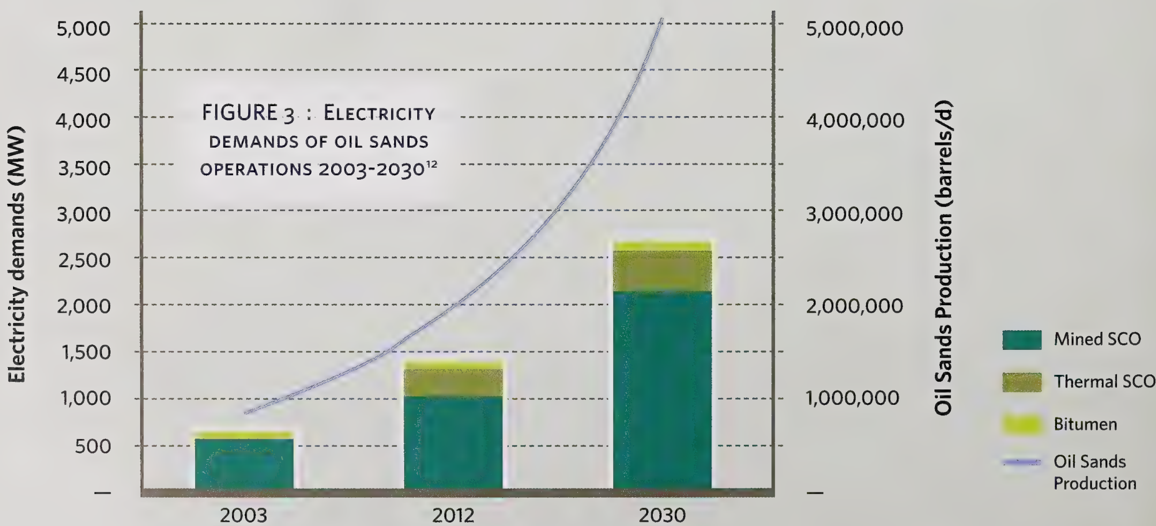



Figure 3, above, indicates how the power demands of oil sands operations (columns) are closely linked to production levels (represented by the line). Based on an extrapolation from growth trends in Alberta's economy, electricity demand in this sector is expected to more than double during the period 2003-2012 and could reach 3200 MW by 2030, based on the forecast production of 5 million barrels per day (ACR, 2004[13]). SCO is synthetic crude oil.

10 *AESO, 2007a (Table 2)*
11 *AESO, 2007a*
12 *Ordorica, 2007*
13 *ACR 2004*

# 3 Options for meeting Alberta's needs

## 3.1 Overview

This chapter discusses the major options available to the Alberta marketplace in responding to the need for new supply outlined in Chapter 2. It provides an initial basis for comparing nuclear power. Details of issues specific to nuclear power are discussed in subsequent chapters.

This chapter provides context – it is not an exhaustive analysis of all available technologies. And as Chapter 2 makes clear, the choice of which technology to pursue is made by private, investor-owned companies, not government.

Each supply option has its pros and cons on the long list of characteristics that are relevant to evaluating its ability to supply Alberta's needs. These include reliability, availability, cost, environmental impact, and so on. No single option is 'perfect' when all the criteria are considered. Some parameters, like the cost patterns over time (such as the difference between up-front and on-going costs) are more directly relevant for private investor-owned companies. Others, such as environmental impacts, have broad societal importance. However, all parameters have an impact on Alberta's citizens as well as on electricity consumers in the province.

The following sections consider basic pros and cons of various supply alternatives.

## 3.2 Nuclear

This section provides a high-level overview of nuclear power in order to compare it with other available technologies. The various aspects of nuclear technology and safety are discussed in detail in subsequent chapters.

### TECHNOLOGY

- Nuclear power is based upon energy generated by fissioning ("splitting") heavy elements such as uranium. This energy is transported away from the reactor to a conventional steam-generating thermal cycle. The nuclear fuel is either enriched uranium or, in the case of the Canadian CANDU reactors, un-enriched natural uranium.

### ENVIRONMENTAL IMPACT

- Nuclear reactors do not have any carbon dioxide emissions when operating.
- On a life-cycle basis[14], $CO_2$ emissions from nuclear power are similar to those from wind power and are associated mainly with uranium mining and nuclear fuel production. These life-cycle $CO_2$ emissions would be substantially reduced if modern enrichment technology is used. (See section 5.2.2.)
- As with any thermal (steam-producing) plant, nuclear plants require water for cooling.
- Nuclear power plants have the smallest 'footprint' in terms of the amount of energy generated per hectare of land.
- Used nuclear fuel must be managed over long time periods to ensure that there is no leakage of radioactive material.

### COST

- The upfront capital costs of building a nuclear plant are high. The nuclear fuel is low- cost and, because small amounts of fuel are required, variations in its cost do not affect operating costs to any great extent. Therefore, nuclear is best suited for large-scale generating units where the initial capital costs can be spread over many hours of low-cost operation.

14 *"Life-cycle" analysis considers all the environmental impacts of a facility, through manufacturing equipment, construction and installation, operations and eventual decommissioning.*

- The cost of energy from nuclear plants typically ranges from 3.5 to 6.0 cents per kW.h.[15]

#### OPERATING CONSIDERATIONS

- Nuclear plants have high capacity factors, meaning they are available to meet demand around the clock. Typically, availability for the latest generation of plants ranges between 90% and 95%.
- Nuclear units must be sited where there is cooling water. This affects planning for transmission facilities to connect them to the grid.

## 3.3 Supply options – fossil fuels

This section provides a high-level overview of major supply options using fossil fuels. Data for the various options is summarized in Table 1.

### 3.3.1 Coal - conventional

#### TECHNOLOGY

- Basic coal technology, using pulverized coal to produce heat that drives steam turbines, is well established in Alberta. The thermal efficiency of coal plants (i.e., the energy extracted per unit of fuel) has been increasing. Newer plants use 'supercritical' technology - in other words, steam at higher heat. 'Ultra-supercritical plants' have not yet been commercially proven, but would improve efficiency and reduce environmental impacts further.

#### ENVIRONMENTAL IMPACT

- Major environmental issues relate to air pollutant emissions, carbon dioxide emission, water use and coal extraction.
- Coal releases more $CO_2$ than other forms of fossil fuel per MW hour of energy produced.
- As with any thermal (steam-producing) plant, coal plants require water for cooling.
- Coal for Alberta's generating stations is extracted through surface mines. Land is taken out of service before being reclaimed and returned to agricultural or other uses.

#### COST

- The upfront capital costs of building a plant tend to be high. Coal's cost benefits come from the abundance of Alberta's sub-bituminous coal which provides inexpensive fuel. Therefore, coal is best suited for large-scale generating units (typically 400 MW and higher), since the initial capital costs can be spread over many hours of low-cost operation.
- Energy from conventional coal plants typically ranges from 6.3 to 6.4 cents per kW.h

#### OPERATING CONSIDERATIONS

- Conventional coal plants tend to have high capacity factors, meaning they are available to meet demand around the clock. Typically, availability for the latest generation of plants ranges between 85% and 90%.
- Coal units must be sited where there is a combination of fuel and water. This affects planning for transmission facilities to connect them to the grid.

### 3.3.2 Coal with carbon capture and storage

#### TECHNOLOGY

Today there are three main approaches to removing $CO_2$ from coal-plant emissions.

- *Pre-combustion capture* in which $CO_2$ is scrubbed from synthetic fuel (i.e., gas produced from coal or other carbon sources) during manufacture.
- *Post-combustion capture* in which $CO_2$ is removed from flue gases after coal has been burned for power, using chemical absorption.
- *Oxyfuel combustion* in which purified oxygen is used to burn the coal. This process produces a highly concentrated stream of $CO_2$ and water vapour.

15 *IEA, 2005; ARC/INL, 2008; PSIRU, 2005*

The $CO_2$ can then be injected into underground storage after the water has been removed. This technology is currently in the advanced demonstration phase. It could be retrofitted on integrated gas combined cycle plants (See 3.3.3)

**ENVIRONMENTAL IMPACT**

- These technologies are capable of removing a significant proportion of the $CO_2$ produced by burning coal. One potential concern is the long-term underground storage of carbon to ensure it does not re-enter the atmosphere or induce seismic activity.
- Mining and water use are similar to conventional coal.

**COST**

- Carbon capture and storage greatly increase the cost of energy from coal units, almost doubling it to about 11.9 cents per kilowatt hour (kWh).

**OPERATING CONSIDERATIONS**

- Conceptually, coal with carbon capture has similar operating characteristics to conventional coal. However in all likelihood this new technology will experience operational hiccups as it is scaled to commercial levels.

## 3.3.3 Integrated Gasification Combined Cycle (IGCC)

**TECHNOLOGY**

- IGCC is a new technology that involves turning coal (or other sources, such as biomass) into a synthetic gas. The gas is then used in a two-stage process. First, the gas is burned to run a turbine generator, then waste heat from this combustion generates additional electricity via a steam turbine.
- Relatively few IGCC plants are in operation world-wide at this time, although many new units have been announced.

**ENVIRONMENTAL IMPACT**

- As mentioned, IGCC plants can be fitted with carbon-capture technology. They are also more effective at removing other pollutants such as sulphur, nitrous oxides, particulates and mercury, so their overall environmental performance is better.
- Water use and mining impacts are similar to conventional coal.

**COST**

- IGCC plants are more expensive than conventional coal plants. However, it is less expensive to add carbon capture to an IGCC plant, so it can produce energy at a lower cost than a pulverized-coal-burning unit with carbon-capture added. The cost of electricity from an IGCC plant without carbon capture is about 7.8 cents per kWh. With carbon capture, it is 10.3 cents per kWh.

**OPERATING CONSIDERATIONS**

- As with other technologies that are coal-based, IGCC plants need to be relatively large units (400 MW) and are better suited for meeting base load. As there are few units in commercial operation worldwide there will in all likelihood be operational hiccups as the technology is scaled to commercial levels.

## 3.3.4 Natural Gas

**TECHNOLOGY**

- Natural Gas Combined Cycle (NGCC) is a mature technology that also employs a two-step process to use waste heat. The use of natural gas for generation has grown substantially in Alberta and in North America over the past decade.

**ENVIRONMENTAL IMPACT**

- Natural gas has a higher energy content and lower carbon content than coal. In combination with the efficiency of the combined-cycle process, this means natural gas produces significantly less $CO_2$ than coal technologies do.
- Its lower sulphur content and absence of mercury also make it a 'cleaner-burning' fuel. (However sulphur dioxide is emitted at the natural-gas-processing stage.)
- Natural gas units require significantly less water than coal units.

### COST

- Natural gas units are relatively inexpensive in terms of upfront capital costs. Their operating costs are driven largely by the price of natural gas, which tends to be more variable than the price of coal. The cost of NGCC electricity, assuming natural gas priced at $7.10 per gigajoule, is 6.8 cents per kWh without carbon capture and 9.7 cents per kWh with carbon capture.

### OPERATING CONSIDERATIONS

- The 'on-off' flexibility of natural gas units has traditionally made this technology particularly useful in meeting peak load. Recently, natural gas-fired generation has been used more frequently to meet base load. However, cost considerations driven by natural gas prices may limit future developments to peaking applications.
- Natural gas units can be easily sited close to where the output is needed.

## 3.4 Supply options – renewable energy

Renewable energies are, by definition, sustainable and are also commonly considered to be $CO_2$-neutral (although from a complete life cycle perspective they are not completely neutral). This section outlines considerations in using various renewable technologies for electricity generation.

### 3.4.1 Wind power

#### TECHNOLOGY

- Currently, approximately 500 MW of wind capacity is installed in Alberta, and applications for more than another 10,000 MW have been submitted.[16]
- Most planned or active wind projects target southern Alberta where wind energy is the highest.
- Alberta has a substantial potential for wind power.[17]

#### ENVIRONMENTAL IMPACT

- Wind power has no air emissions or water requirements.
- With older technologies, there is some evidence of impact on bird migration.
- Wind turbines may create 'visual pollution' issues related to siting in sought-after recreational, residential or tourist areas.
- $CO_2$ is emitted during manufacture and transportation of turbines and associated equipment, and for the substantial amounts of concrete required in construction and installation of wind farms.

#### COST

- Cost of wind-generated electricity ranges from 4.6 to 14.4 cents per kWh.[18]

#### OPERATING ISSUES

- Individual wind units have a relatively low capacity factor, because wind speeds and availability vary. So, for example, a 1-MW wind turbine is likely to be available, on average, 30 to 40% of the time. This means it takes more than one MW of wind capacity to substitute for one MW of coal or natural gas capacity.
- Distributing wind farms over different geographic areas combined with effective wind forecasting could help offset this effect. This would require additional transmission and wind forecasting capacity.
- System operations and reserve capacity must be carefully planned to ensure continued reliability if wind energy is to contribute a more significant proportion of electricity.

### 3.4.2 Solar power

#### TECHNOLOGY

There are two different types of solar energy systems:

- *Photovoltaic technology* produces electricity directly from sunlight and is currently the most advanced solar technology. Solar panels can be mounted

16 GOA, 2008
17 IEA, 2005
18 IEA, 2005

on tracking systems to increase their exposure to sunlight. Photovoltaics are appropriate for small off-grid distributed electricity generation.

- *Concentrating solar power plants* use reflectors to focus a large amount of sunlight in a small area to produce heat. Concentrating systems have increased dramatically in development and popularity worldwide. Unlike photovoltaic technology, concentrating solar power facilities are suitable for large-scale electricity generation, using solar energy to produce steam to drive power turbines. As an example, a solar project under construction in California will produce 553 MW by 2011.[19]

## ENVIRONMENTAL IMPACT

- There are no emissions associated with solar, except from a life-cycle perspective in the production and transportation of solar equipment.
- Solar power plants require a large footprint of land, generating less electricity per acre than fossil fuel plants.

## COST

- The cost of photovoltaic and concentrating solar systems has followed a continuously decreasing trend, making them progressively more attractive on an economic basis. However, this trend line appears to have flattened out in recent years.[20]
- Solar energy currently costs approximately 20.9 to 74.3 cents per kWh.[21]

## OPERATING ISSUES

- Alberta has large potential for concentrating solar power plants due to its natural endowment of high insolation values (hours of sunshine) – higher than Germany and France where solar applications have been increasing. The amount of solar energy available in Alberta varies widely by location in the province and season.
- There is also large potential in Alberta for photovoltaic-based distributed energy for residential and small commercial applications.[22]
- Solar energy is variable in its occurrence and requires storage and/or back-up generation.
- In Canada, solar energy is currently used mainly for small off-grid applications. This type of use has little impact on the transmission grid. However, as with wind power, a higher proportion of solar generation would require system planning and increased transmission capacity to ensure continued reliability.

# 3.4.3 Hydroelectricity

## TECHNOLOGY

- Hydroelectricity currently contributes 900 MW to the Alberta grid.
- Forecasts suggest only moderate additions within the next 20 years, including 200 MW of small hydro before 2024.[23]
- Two significant projects are currently being discussed: a 100-MW project at the Dunvegan site on the Peace River (now in the approval process) and a 1200–1300 MW project on the Slave River. However, both of these will have long lead times and the actual in-service dates, should the projects go ahead, are uncertain.

## ENVIRONMENTAL IMPACT

- Hydro projects are emissions-free, except from a life-cycle perspective due to plant production, transmission and construction, and use a renewable resource. However, they may affect water regimes and fisheries significantly and may require flooding or affect downstream environments.

## COST

- Hydro projects are capital-intensive projects, and upfront costs vary widely depending on the site and scale of the project.
- Cost of energy from hydro varies depending on the site.

## OPERATING ISSUES

- Hydro units are 'instant-on' and so adapt well to being used as peaking units.
- Flexibility in siting is limited, and transmission must be built to reach the resource.

19 *Abengoa, 2008*
20 *IEA, 2007*
21 *ARC/INL 2008*
22 *IEA, 2005*
23 *AESO, 2005.*

- Water flows vary seasonally and tend to be lower in winter, when demand for electricity is high.

### 3.4.4 Biomass

#### TECHNOLOGY

- Biomass-based electricity is fuelled by wood, agricultural residue, waste, or dedicated energy crops. There is increasing interest in using municipal waste as a source.
- Generation using biomass is generally most effective where the feedstock is readily and continuously available as an industrial/agricultural waste stream, and where waste heat from generation can be recovered and used in manufacturing. (Such opportunities may exist, for example, in the forestry industry.)

#### ENVIRONMENTAL IMPACT

- Although biomass-fuelled electricity may be considered $CO_2$-neutral based on the life cycle analysis of the feedstock, other emissions such as particulates and sulphur compounds are of concern. Transporting feedstock generates emissions and, as with other generating technologies, there are emissions associated with equipment construction and transportation.

#### COST

- The current cost of biomass-fuelled electricity depends on factors such as the proximity and cost of feedstock source, scale, and grid accessibility. Transporting low-value, low-energy-density feedstock is expensive if it is required.

#### OPERATING ISSUES

- Given the limits on feedstock availability, biomass units are likely to be relatively small additions to the grid.

### 3.4.5 Geothermal

#### TECHNOLOGY

- Alberta has moderate sources of hydrogeothermal energy in the Western Canada Sedimentary Basin as well as in the northwest portion of the province.[24] The resource in the northwest is located at greater depths (5 km) and the technology for using it is still at the demonstration stage.
- The promising sources identified are remote from any current demand for power or grid transmission lines.

## 3.5 Demand-side management

Alberta, like most electric systems, likely has potential to reduce or modify electricity demand in both the commercial and the residential sectors. 'Demand-side management' initiatives are aimed at modifying demand, thereby reducing the need for new generation capacity.

Various market-based planning and technology approaches have been used in other electric systems since the 1970s in order to reduce demand and/or shift it to times when there is excess generation capacity available. For example, through pricing and appliance timer technology, residential laundry demand can be shifted from peak-demand times of day to lower-demand periods overnight. The relative cost as well as the effectiveness of demand-side management programs depend on a large number of factors, such as electricity prices, the availability of substitutes and the specifics of implementation.[25] In general, higher electricity prices suggest more scope for demand-side management, as the higher prices provide more 'room' for alternative technologies and changing consumer behaviour.

This is one area of 'supply' in which government action, via policy or strategy, would be required in order to develop resources. For the most part demand-side management results from a government or regulatory agency policy or regulation and not from market initiatives.

24 *Majorowitcz, 2008*
25 *Loughran & Kulick, 2004*

## TABLE 1 : Comparison of fossil fuel plants

| | Subcritical | | Supercritical | | Ultra-supercritical | | IGCC | | NGCC | | Oxyfuel |
|---|---|---|---|---|---|---|---|---|---|---|---|
| With/without $CO_2$ capture | NO | YES | NO | YES | NO | YES | NO | YES | NO | YES | YES |
| Plant cost ($/kW$_{\text{Net capacity}}$) | 1549 | 2895 | 1575 | 2870 | 1641 | 2867 | 1813 | 2390 | 554 | 1172 | 2930 |
| Power cost ($/MWh) | 64.0 | 118.8 | 63.3 | 114.8 | 64.5 | 106.0 | 78.0 | 102.9 | 68.4 | 97.4 | 109.0 |
| $CO_2$ emissions (kg/MWh$_{Net}$) | 855 | 126 | 804 | 115 | 706 | 98 | 796 | 93 | 361 | 42 | 65 |
| $SO_2$ emissions (kg/MWh$_{Net}$) | 0.35 | Nil | 0.33 | Nil | 0.29 | Nil | 0.05 | 0.04 | Nil[j] | Nil[j] | 0.04 |
| $NO_X$ emissions (kg/MWh$_{Net}$) | 0.29 | 0.43 | 0.27 | 0.39 | 0.24 | 0.33 | 0.22 | 0.22 | 0.02 | 0.03 | 0.38 |
| Particulate emissions (kg/MWh$_{Net}$) | 0.05 | 0.08 | 0.05 | 0.07 | 0.04 | 0.05 | 0.03 | 0.03 | Nil | Nil | 0.009 |
| Mercury emissions (×10-6 kg/MWh$_{Net}$) | 4.77 | 7.09 | 4.53 | 6.47 | 3.94 | 5.53 | 2.33 | 2.69 | Nil | Nil | 0.82 |
| Raw water usage ($M^3$/MWh) | 2.57 | 5.04 | 2.25 | 4.34 | 1.82 | 4.09 | 1.42 | 1.86 | 1.02 | 1.84 | 2.95 |

Table 1 is from ARC/INL 2008 and compares the characteristics of different kinds of fossil-fuel plants, both with and without carbon capture/storage. "Subcritical," "Supercritical" and "Ultra-supercritical" represent conventional pulverized-coal-burning units that use increasingly high steam pressures. Costs are in 2007 U.S. dollars.

# 4 An overview of nuclear power

## 4.1 Overview

This chapter provides background on nuclear power: how it is used to generate energy; what kinds of reactor technologies exist; and how it has developed historically.

As Figure 4 shows, a nuclear power plant is very similar to a fossil power plant where heat produces steam that drives a turbine-generator. The main difference is how the initial heat is produced. In a nuclear plant, it comes from nuclear fission.

## 4.2 Nuclear fission

At the heart of each atom of any element is a nucleus, made up of protons and neutrons. In one naturally occurring form of uranium, known as U-235, the nucleus is likely to undergo fission when bombarded by neutrons with low kinetic energy. "Fission" means the nucleus breaks into two fragments, as shown in Figure 5. In turn, these fragments release energy (in the form of radiation), and also at least two more neutrons.

FIGURE 4 : COMPARISON OF NUCLEAR PLANTS WITH CONVENTIONAL GENERATING PLANTS

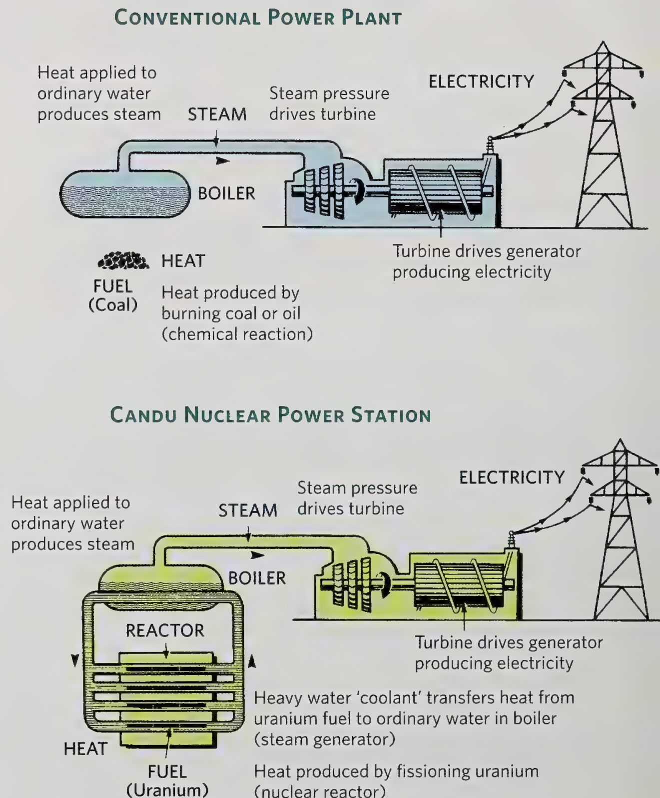
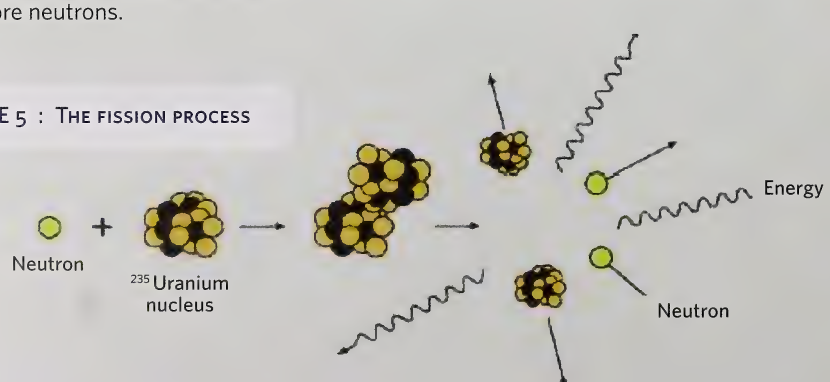



FIGURE 5 : THE FISSION PROCESS



When the mass of all the products left after fission has taken place is added up, the result is very slightly less than the mass of the original neucleus. Part of the mass has become energy. Einstein's famous equation, $E=mc^2$, determines just how much energy can be released by a very small mass.

Under the right conditions, the neutrons released by the break-up of the nucleus go on to bombard other nuclei, causing more fission events. By arranging material appropriately a self-sustaining, controlled chain reaction can be produced.

Almost all commercial nuclear reactors are thermal reactors. This means the neutrons released by fission are 'slowed down' by passing them through a relatively light material such as hydrogen, deuterium or carbon. In turn, this makes the neutron more likely to contact another uranium nucleus and cause it to fission.

These lighter materials are called moderators. They can be light water (ordinary water composed of hydrogen and oxygen), heavy water (a rarer form of water found in nature which is composed of deuterium and oxygen), or graphite (carbon).

Energy released from fission causes the uranium fuel elements to heat up. A flow of liquid or gas fluid – the coolant – flows over the fuel elements, picking up heat from the fuel and using it to boil water into steam to power the generator.

It is a common misconception that a nuclear reactor has the potential to explode like an atomic weapon. However the technologies for power and for weapons are fundamentally different. A nuclear weapon is designed to release energy extremely quickly and in enormous quantities. It would be physically impossible to generate such large and rapid energy releases using the arrangement of fuel required to sustain a controlled fission chain reaction over the long periods of time (hours, days and years) needed to produce electric power in a nuclear reactor.

### 4.2.1 Types of nuclear reactor

Reactor types vary according to the moderator used to control the speed of neutrons, the coolant employed to transfer heat to the generating cycle, and by the degree of U-235 enrichment in the nuclear fuel. These characteristics are inter-related: natural uranium fuel without enrichment needs a more effective moderator that can slow neutrons to a speed where more fission events can take place.

There are 443 reactors operating around the world today, and they can be classified into the following broad categories:

- The **Pressurized Water Reactor** (PWR) – approximately 60% of reactors world-wide. This reactor type uses ordinary 'light' water as a moderator and also as the coolant. It has two separate coolant loops, one to remove heat from the reactor and the other to provide steam to a turbine that drives an electrical generator. The primary loop (which is in closest contact with the reactor core) is maintained under high pressure to keep it from boiling.
- The **Boiling Water Reactor** (BWR) – approximately 20% of reactors world-wide. This type also uses light water as a moderator and coolant, but has a single coolant loop in which the water is allowed to reach boiling temperature and produce steam.
- The **Pressurized Heavy Water Reactor** (PHWR) – approximately 11% of reactors world-wide. This type is predominantly based upon the CANDU reactor developed in Canada. It uses heavy water as a moderator and coolant, and natural uranium fuel. Like the PWR it uses two separate coolant circuits, one to remove heat from the reactor and the other to provide steam to a turbine that drives an electrical generator. The primary loop cooling the reactor is maintained at high pressure to limit the amount of boiling.
- **Gas cooled reactors** (GCR) – A few reactors of this type have operated commercially, mainly in the UK. These reactors use solid graphite as a moderator and gas (either carbon dioxide or helium) as the coolant removing heat from the nuclear fuel. The gas reactors in the UK are being phased out. However, as will be discussed later, new gas reactors are either being developed or considered because they could provide high-temperature heat along with a wide range of potential process applications.

Table 2 summarizes the differences between these reactor types.

TABLE 2 : Characteristics of different types of nuclear reactor

| Reactor Type | Coolant used | Moderator | Fuel U-235 Enrichment |
|---|---|---|---|
| Light-Water Reactors (Includes PWR, BWR and VVR) | Light water | Light water | 3% to 5% |
| PHWR | | | |
| Current CANDU | Heavy water | Heavy water | 0.71% (Natural) |
| Advanced CANDU | Light water | Heavy water | ~2% to 2.4% |
| Gas Cooled | Helium Gas | Graphite | 10% to 20% |
| RBMK (Soviet) | Light water | Graphite | 1.2% |
| LMFBR* | Liquid sodium | None | 10% to 20% |

Reactor types are characterized primarily by the moderator and coolant employed and by the degree of U-235 enrichment in the nuclear fuel. Enrichment is a process of increasing the percentage of U-235 in fuel, compared with the more stable and more common form of uranium, U-238.

*LMFBR: Liquid Metal Fast Breeder Reactor. These were not discussed in detail in the text because so few are in operation. A "breeder reactor" produces more fissile material (plutonium) than it consumes.

## 4.2.2 The development of nuclear power

Electricity generation using nuclear power is a well-established technology, dating back more than 50 years to the early prototype commercial power plants in the UK and USA in the mid-1950s.

Commercial nuclear power development started after World War II when it was recognized that the large energy release associated with fissioning of atoms could be applied to peaceful uses, in particular the generation of electricity.

These early developments investigated different nuclear reactor concepts, including designs with light water, heavy water, gas and liquid metal coolants, and various types of nuclear fuel design. A number of countries undertook development of reactors in the early stages, including the United States, Canada, the UK, France and Russia.

### THE USA

In the United States, commercial nuclear reactor designs very rapidly focused on compact light-water-cooled designs based upon the successful development of naval propulsion reactors. These compact designs required fuel to be enriched so that it has a higher content of the U-235 isotope. These naval propulsion designs developed into the successful light-water reactor designs – Pressurized Water Reactor (PWR) and Boiling Water Reactor (BWR) – that have become the predominant commercial power reactors currently in use around the world.

### CANADA

Development of the Canadian CANDU design was influenced by two factors:

- The country's resources of uranium led to an early decision not to rely on uranium enrichment since

costly enrichment technology would have to be acquired from abroad. Instead, Canada's nuclear program was based on natural uranium fuel.

- Because natural uranium has less of the U-235 isotope, a more efficient design for slowing down the neutrons was needed. Canada had developed expertise with heavy water during World War II, and this was incorporated into reactor design.

CANDU reactors operate in Canada and a number of countries around the world. The majority of CANDU reactors in Canada are located in Ontario as a result of the collaboration between the provincial utility Ontario Hydro and the Federal Crown Corporation, Atomic Energy of Canada Limited (AECL), in developing and constructing the reactors in the period between 1960 and 1972.

#### EUROPE

In the UK and France early developments focused on two concepts:

- Magnox reactors used gas as a coolant and graphite to moderate neutron speed.
- The Steam Generating Heavy Water Reactor used a combination of light water for cooling and heavy water as a moderator.

Neither of these two concepts was successful and the designs were abandoned. The UK continued development of gas-cooled designs. The Advanced Gas Reactor has been operated commercially but is to be phased out.

Following the oil crisis of the early 1970s, France committed to licensing the PWR technology offered by Westinghouse in the U.S. and rapidly built the second-largest nuclear power program in the world.

#### SOVIET UNION

In the early period, the Soviet Union developed a graphite-moderated/water cooled design, referred to as the RBMK reactor. This design did not require tight tolerances and could be constructed relatively quickly and at low cost. These reactors were being deployed in a very ambitious program which was rapidly halted following the accident at the Chernobyl Unit 4 reactor in 1986.

Subsequently, Russia has focused reactor development and deployment on a PWR-type of reactor design known as VVER. Reactors of this type are found in former Soviet-bloc eastern European countries.

#### ASIA

Asia has seen a steady increase in the number of reactors brought into service over the past three decades. Japan has licensed U.S. light-water technology and operates a significant number of PWR and BWR reactors. In the past decade the large Japanese conglomerates Toshiba, Hitachi and Mitsubishi have either bought U.S. vendors or formed alliances with them to develop new advanced Generation III reactor designs.[26]

South Korea has also developed a significant nuclear power program focused on PWR and CANDU reactors. Additionally, South Korea has developed an advanced Generation III design. More recently China has embarked upon a very ambitious nuclear power program based primarily on PWR technology, but also including two CANDU units. India with its large population and burgeoning economy has also embarked upon a major expansion of its nuclear power program. India's program primarily uses domestically developed reactors based upon CANDU technology.

### 4.2.3 Recent deployment of nuclear power generation

Figure 6 shows the number of reactors built in Canada and around the world from 1965 to 2007. Since the early 1990s no new reactors have been brought into service in North America. In the United States, this reflected the financial impact of the Three Mile Island[27] accident, which terminated orders for new nuclear units, led to the cancellation of a large number of units and resulted in significant regulatory delays in bringing into service any reactors that were not cancelled.

It is interesting to note that the accident at Three Mile Island Unit 2 in 1979 significantly dampened the growth of nuclear power in the U.S. but had very little impact outside of the U.S. In fact non-U.S. growth in nuclear power actually accelerated after the Three Mile Island accident.

26 *Generation III reactor designs are discussed in section 4.3.*
27 *Details of the Chernobyl and Three Mile Island events are covered in Chapter 6 on nuclear safety.*

Canada installed 12 nuclear units between 1979 and 1992, when the Darlington reactors were brought into service. However, there have been no units constructed in Canada since then. This was largely because of cost issues. Darlington incurred large cost overruns due to interest charges when construction schedules were set back. Subsequently, the Ontario government felt that low demand growth did not justify the addition of more nuclear units.

### 4.2.4 Current situation

As of mid-2008, construction is underway on projects that will increase the number of reactors world-wide to approximately 491 within the next six years. The distribution and types of nuclear reactors operating in different regions of the world are summarized in Table 3.

Canada has a total of 22 nuclear power reactors currently in service, of which 20 are in Ontario (with 18 operating and 2 in a laid-up state) and 1 in each of Quebec and New Brunswick. All of these reactors are CANDU Pressurized Heavy Water reactors.

Additionally there are research reactors located at AECL's Chalk River Laboratory (the 135-MW NRU reactor and a low-power 100W reactor ZED-2). Other research reactors are located at universities, including the second-largest in North America at McMaster University, and a number of smaller SLOWPOKE research reactors, including one at the University of Alberta.

TABLE 3 : TYPES OF NUCLEAR REACTORS IN OPERATION

(AS OF MID-2008)

| REGION | REACTOR TYPE | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Light Water | | | Pressurized Heavy Water | | Gas Cooled | RBMK (graphite cooled) | LMFBR* | Total |
| | PWR | VVER | BWR | CANDU | OTHER | | | | |
| North America | 69 | | 35 | 22 | | | | 1 | 127 |
| Western Europe | 90 | 2 | 19 | 2 | | 18 | | 1 | 132 |
| Eastern Europe | | 50 | | | | | 16 | 1 | 67 |
| Asia | 49 | | 40 | 22 | | | | | 111 |
| Rest of World | 4 | 1 | | 1 | 1 | | | | 7 |
| **SUBTOTAL** | 212 | 53 | 94 | 47 | 1 | 18 | 16 | 3 | |
| **TOTAL** | **265** | | **94** | **48** | | **18** | **16** | **3** | **444** |

*LMFBR: Liquid Metal Fast Breeder Reactor.

FIGURE 6 : DEPLOYMENT OF COMMERCIAL NUCLEAR REACTORS SINCE 1965[28]

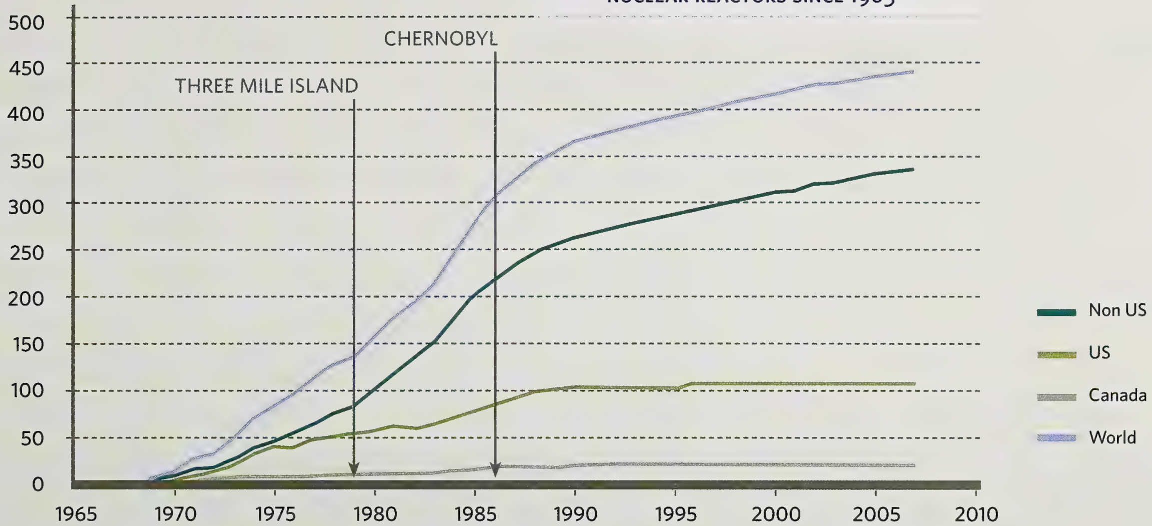



Figure 6 indicates that deployment of new nuclear power plants leveled off in North America in the mid-1980s after events at Three-Mile Island and Chernobyl (discussed more fully in Chapter 6), but has continued to climb in the rest of the world.

## 4.3 New nuclear reactor designs

A new generation of nuclear reactor designs, often referred to as Generation III reactors, are about to be deployed over the next decade. These include:

- The Advanced CANDU Reactor (ACR-1000) designed by Atomic Energy of Canada Ltd.,
- The AP-1000, an advanced PWR designed by Westinghouse,
- The EPR, an advanced PWR designed by the French nuclear company, AREVA, and
- The ESBWR, an advanced boiling water reactor designed by General Electric.

These reactors feature enhanced safety, including 'passive' safety systems[29], and improved economics. Passive features do not rely on external sources of power to keep them functioning. Instead they rely on natural processes such as natural circulation (associated with temperature differences in fluids) steam generation and steam condensation to remove heat from systems.

Also under development is a new generation of reactors, often referred to as Generation IV reactors, which also incorporate improved safety and non-proliferation features. (The latter make it even more difficult to divert materials for non-power generation purposes). The most advanced of these is the Pebble Bed Modular Reactor (PBMR) currently under development in South Africa. This high-temperature gas reactor uses graphite as a moderator and helium as a coolant and has ball-shaped graphite-coated fuel (the "pebbles"). The reactor is designed for flexible applications such as producing either 165 MW of electrical power or 400 MW of thermal heat for process applications (e.g. hydrogen generation, water desalination or oil sands recovery).

28 *Source: American Nuclear Society, Nuclear News, Reference Issue, July 2008*

29 *Safety is discussed in more detail in Chapter 6.*

## 4.4 Environmental aspects of nuclear power

This section discusses the air and water aspects of nuclear power. Issues specifically related to nuclear fuel and waste are discussed in subsequent chapters.

### 4.4.1 Air

Nuclear power has attracted renewed interest recently because it does not emit carbon dioxide ($CO_2$) or other air pollutants during operation, unlike fossil-fuel-based forms of electricity generation. Considering the entire life cycle (including mining, processing, uranium enrichment, fuel fabrication and transport), the emission of $CO_2$ from nuclear power generation is similar in magnitude to the life-cycle emissions from renewable energy sources such as wind power.

The majority of the life-cycle emissions for nuclear power result from mining and enrichment, assuming the energy these processes require comes from fossil-fuelled power stations. However, if uranium enrichment used the more efficient centrifuge process and nuclear generated electricity in place of fossil fuelled generation, then life-cycle $CO_2$ emissions from nuclear power would be substantially lower.

### 4.4.2 Water

Nuclear power plants, like fossil-fuelled power plants, require cooling to condense the steam exiting the large turbines. This cooling is provided by cold water flowing through the tubes of the turbine condenser. The heat transferred to the condenser cooling water is released to the environment by one of three possible means:

- *Once-through cooling* extracts water from a river, lake or ocean. The amount of water extracted in a year for the reference 800-MW nuclear plant would be in the range of 600 to 1400 million cubic meters. Of this, about 10 million cubic meters would be lost to evaporation while the rest was returned to the body of water. Once-through water cooling has various effects on the environment: damage to aquatic life at intakes; discharge of warmer water into the parent body of water; and the impact of chlorine, which is used to control corrosion and accumulation of microbes and minerals, on aquatic life.
- *Heat release to the atmosphere by evaporative cooling towers.* For the 800-MW reference plant, this type of cooling would require 20 to 30 million cubic meters of water, of which about 17 million cubic meters would be lost to evaporation. Environmental impacts arise from periodic blow-down discharge of water containing chlorine and other chemicals used to control corrosion and the accumulation of microbes and minerals.
- *Heat release to the atmosphere by dry air fan cooling.* Forced air cooling does not require any water for cooling but does consume some of the electricity generated by a power plant to drive the fans. Although less efficient than direct water cooling or evaporative cooling, this is a good option for areas where there is limited water supply.

The volumes of water required by various cooling systems and the environmental impacts are similar to those for fossil-fuelled plants. Cooling water is not in contact with nuclear fuel and so cannot release radioactivity into the environment.

# 5 Nuclear fuel management

## 5.1 Overview

This chapter looks at the fuel used for nuclear reactors: how it produces energy; how it is mined and milled; how it operates in a reactor; and how it is disposed of. These stages make up the complete 'nuclear fuel cycle.'

As discussed in Chapter 4, the majority of power reactors operating today are cooled either by light water (PWR, BWR) or heavy water (CANDU, PHWR). The fuel for these reactors is made up of two principal components: ceramic pellets of uranium dioxide ($UO_2$), and zirconium alloy tubes that encase the pellets and are referred to as either the fuel sheath or cladding.

For purposes of this report, a hypothetical nuclear unit of 800 MW has been used, as being most comparable to a base-load coal plant in the Alberta system. This does not correspond to any particular nuclear reactor design currently on the market and is not meant to suggest a specific type of plant. Rather this hypothetical nuclear unit is used to compare it to standard supply-side solutions.

## 5.2 The nuclear fuel cycle

The nuclear fuel cycle consists of two main parts:

*Front-end processes:*

- mining;
- processing the ore into a form suitable for manufacturing fuel;
- enriching the concentration of uranium-235 (for reactors requiring enriched fuel);
- fabricating the nuclear fuel pellets, fuel bundles and assemblies that are inserted into the reactors.

*Back-end processes:*

- storing the used fuel discharged from reactors;
- ultimately disposing of the waste products.

Figures 7 and 8 show the difference between natural-uranium and enriched-uranium fuel cycles, which takes place primarily during the front-end processes. For the enrichment process, an intermediate conversion step produces uranium hexafluoride ($UF_6$), which facilitates the concentration of uranium-235. Then a second conversion process produces uranium dioxide ($UO_2$) powder, the product required for manufacturing the uranium fuel pellets.

The figures also show the typical mass of materials involved at different stages of the fuel cycle.

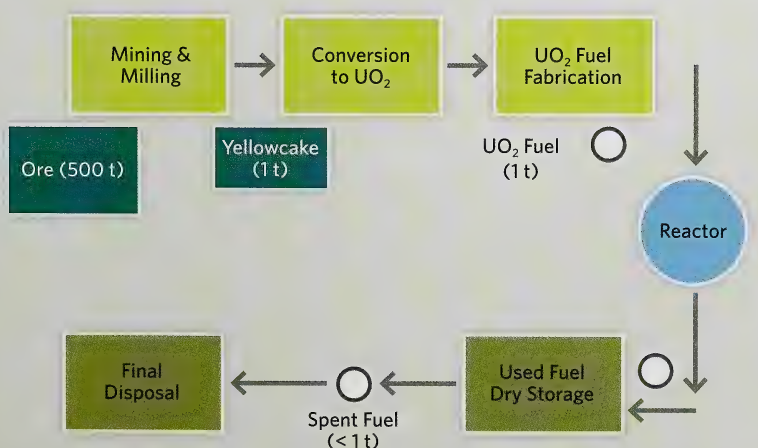



FIGURE 7 : OPEN FUEL CYCLE (CANDU REACTOR – NATURAL URANIUM FUEL)

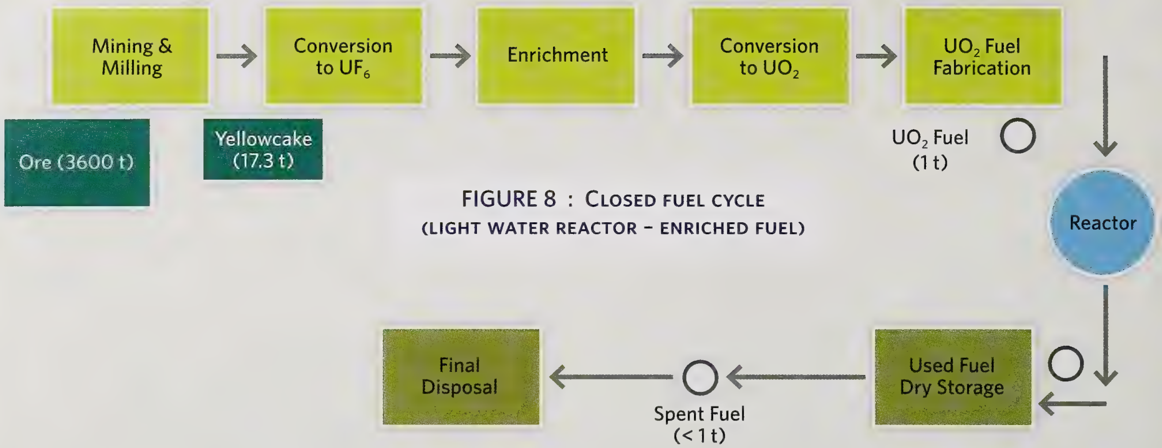



FIGURE 8 : CLOSED FUEL CYCLE (LIGHT WATER REACTOR – ENRICHED FUEL)

Nuclear fuel cycles can also be classified as 'open' or 'closed.' In an open cycle, the fuel is placed in a reactor only once. After discharge it is stored prior to ultimate disposal.

A closed cycle, on the other hand, involves recycling the significant energy content that still remains in the fuel so that fissionable material can be incorporated into newly fabricated fuel. This recycling requires the use of reprocessing technology to separate the true waste material – the very small amounts of fission products – from the material that can be further fissioned to yield energy. Reprocessing and fuel recycling will be discussed later in this chapter.

### 5.2.1 Mining and milling uranium

Uranium occurs widely in the earth's crust, at an average of four parts per million. Like other metals, it forms mineral compounds rather than being found as a pure metal. The distribution of uranium in the earth's crust is not uniform. In certain localities, higher concentrations in ore bodies can be economically mined.

Countries with the largest reserves of uranium ore are Australia, Kazakhstan and Canada. Other countries with significant uranium reserves include South Africa, Namibia, Niger and the USA. World-wide the average grade of uranium ore is 0.2%[30].

Canada is the only country in the world to possess high-grade ore bodies, defined as ore with more than 2% uranium by mass. The McArthur River mine in Saskatchewan has the highest-grade ore found anywhere on earth, at 20.5% on average (This is 100 times the world-wide average ore grade.) The Cigar Lake Mine, currently being brought into service, will have the second-highest-grade ore in the world. By comparison, ore bodies in other parts of the world have grades in the region of 0.01% to 1% (1/20 to 5 times the world average).

In some locations, uranium is extracted through *in situ* leaching, a process in which a solution is injected into the ore body to dissolve the uranium-bearing compounds and then pumped back to the surface for further processing. This process is currently employed, for example, in mining operations in the United States where the ore grade is low.

Typically, mining and milling involves extracting the uranium-bearing ore, crushing and grinding it to coarse particle form and leaching it with an acid to extract the uranium as a solution. After further refining to remove impurities, the uranium is precipitated as $U_3O_8$ powder, referred to as 'yellowcake' because of its colour.

30 *Uranium ore grade is defined as the ratio of the mass of uranium metal produced to the mass of ore mined. Therefore, 10 kg of uranium metal can be produced by mining 1 tonne (1000 kg) of ore with a grade of 1%.*

## 5.2.2 Fabricating reactor fuel

The yellowcake powder is refined and converted either directly to uranium dioxide ($UO_2$) (for use in natural uranium fuel CANDU reactors) or to uranium hexafluoride (UF6) for subsequent enrichment. The U-235 isotope naturally makes up 0.711% of the uranium found in nature. The enrichment process increases this concentration to between 3% and 5%, as required by light-water reactors.

The early enrichment process developed in the United States was based upon gaseous diffusion. Uranium-235 atoms are lighter than uranium-238 atoms, and so diffuse through a membrane barrier slightly more often. However, the separation efficiency of gaseous diffusion is relatively low and the process requires large amounts of energy. In Europe an alternative process based upon centrifuge technology was developed, which has significantly higher separation efficiency and much lower power requirements. The throughput capacity of individual centrifuges is low, and so a large number of centrifuge machines must operate in parallel to yield the required mass of enriched product. Nevertheless, centrifuge separation plants require approximately 25 times less energy to produce the same amount of enriched product as a gaseous diffusion plant. As a result modern enrichment plants employ the centrifuge process[31].

Fuel pellet fabrication involves a number of steps:

- *Powder granulation* involves increasing the effective particle size of the powder so that it will flow more freely. This is necessary in order to produce consistent quality and density of the pressed pellets.
- *Pressing* compacts the $UO_2$ powder to produce uniformly sized cylindrical pellets of relatively low density.
- *Sintering* passes the pellets slowly through a high-temperature hydrogen sintering furnace which increases their density. The process produces hour-glass-shaped pellets, which must be ground with water lubrication to the cylindrical shape needed for insertion into the fuel sheath.
- *Stacking* lines up the pellets end-to-end to the desired length for insertion into the zirconium alloy fuel sheaths. The sheath tube is filled with helium gas and hermetically sealed by welding end caps onto the ends. This forms a fuel element.
- *Fuel bundle assembly* is the final step where fuel elements are arranged in a regular array (cylindrical in the case of CANDU fuel bundles or a square array for light-water reactor fuel assemblies). Structural supports along the length of the fuel elements keep them in a desired spacing and structures at either end hold them together.

In Canada, uranium fuel processing facilities are located in Ontario. Yellowcake produced from mining and milling of uranium ore in Saskatchewan is shipped to Cameco's refinery in Blind River, Ontario. Here it is refined to remove impurities and produce high quality uranium trioxide ($UO_3$). The uranium trioxide is shipped to Cameco's conversion facility in Port Hope, Ontario. Here, it is converted either to uranium dioxide ($UO_2$) for CANDU fuel or to uranium hexafluoride ($UF_6$) which is sent to uranium enrichment facilities around the world.

The uranium dioxide destined for use in CANDU reactors is then sent to Canadian General Electric in Peterborough, Ontario or to Zircatec Precision Industries in Port Hope, Ontario where it is further processed into fuel bundles.

## 5.3 Fuel utilization in a reactor

Inside the reactor, once it is operating, uranium-235 in the fuel pellets undergoes fission as described in Chapter 4, releasing energy. In addition to the uranium-235 fission, some of the uranium-238 (by far the predominant uranium isotope in the fuel) undergoes 'transmutation' – in other words, it captures a neutron to form a new element called plutonium-239. Plutonium-239 undergoes fission just like uranium-235.

This combination of fission and transmutation processes occurs in all operating reactors. In a CANDU fuel bundle, for example, about equal amounts of energy are released from fissioning uranium and plutonium atoms.

The amount of energy produced by nuclear fuel before it is discharged from the reactor is termed the *fuel burnup.*[32] As fuel burnup increases, more of the original uranium-235 is consumed by fission, more plutonium isotopes are produced by transmutation, and more plutonium atoms also undergo fission.

Each fission event, whether it involves uranium or plutonium, produces two fragments from the original

31 *A new process based on laser separation technology being developed in the USA offers even higher separation efficiencies with the potential to extract uranium-235 from the depleted uranium in current enrichment tails (typically containing between 0.2% and 0.3% uranium-235).*

32 *Typical units of measurement for fuel burnup are gigawatt-days per tonne of uranium metal (GWd/tU) or the equivalent unit megawatt-days per kilogram of uranium metal (MWd/kgU).*

atom. Each is one of a number of possible isotopes of lighter elements. These fragments are short-lived, highly ionized[33] and unstable, and they deposit energy in the fuel pellet through interaction with other atoms and by emission of radiation. These unstable isotopes are referred to as *fission products*.

Fission products are the true waste from the fission process, since the uranium and plutonium that have not undergone fission still represent a significant energy source. For example, a new CANDU fuel bundle has approximately 18,800g of uranium metal. On discharge (typically after 8 months), it contains approximately 18,660g of heavy metal, mostly uranium-238, and only about 140g of fission products. In other words, fission or waste products represent only about 0.74% of the original mass of the uranium in the fuel bundle.

Table 4 shows typical fuel utilization and the fission products generated in CANDU and light-water reactors of the same size. For perspective, the table indicates that generating an amount of electricity equal to about 12% of Alberta's 2007 energy consumption could result in less than one tonne of fission or waste products, leaving the heavy-metal component of the fuel available for recycling and reuse.

## 5.4 Managing spent fuel

Once fuel is discharged from the reactor, it is highly radioactive and continues to produce heat through decay of the fission products. The heat energy is only a small fraction of the heat generated in the bundle at full power, but it is sufficient to require continued cooling. This is provided by storage in 'spent fuel bays' – large water-filled pools. (Water provides a shield against all three forms of radiation.[34]) About 10 years after discharge, the heat has decayed to a sufficiently low level that the fuel can be transferred to concrete dry-storage structures in which the fuel is air-cooled.

Used fuel can be recycled to separate the waste fission products from the heavy actinide metals (i.e., uranium, plutonium and other heavy metals). This is an attractive option for maximizing the fission energy from mined uranium. Recycling fuel also has the benefit of significantly reducing the time frame over which final waste products have to be stored. This is because heavy metals have a very long half-life before they decay by emitting alpha particles from the nucleus. The lighter fission or waste products decay more quickly, mainly by emitting beta particles (electrons). Most fission products decay away to the natural background levels of radioactive material found in the earth's crust within approximately 500 to 1000 years.[35]

**TABLE 4 : FUEL USE AND FISSION PRODUCTS**

| | CANDU | LWR |
|---|---|---|
| Electrical power output [MW] | 800 | 800 |
| Thermal efficiency [%] | 33 | 33 |
| Capacity factor [%] | 90 | 90 |
| Fuel enrichment [% U-235] | 0.711 | 3-5 |
| Fuel Burnup [GWd/tonne U] | 7.5 | 30-50 |
| Uranium required per year [tonne] | 106 | 27-16 |
| Uranium yellowcake required per year [tonne] | 124 | 134-132 |
| Mass of 20% grade uranium ore mined per year [tonne] | 530 | 570-563 |
| Mass of 0.2% grade uranium ore mined per year [tonne] | 53,000 | 57,000-56,260 |
| Mass of fission products waste per year [tonne] | 0.796 | 0.81-0.8 |
| Electrical energy generated in a year [GWd] | 263 | 263 |

Statistics are for hypothetical 800-MW light-water and heavy water (CANDU) reactors. GWd = gigawatt-day (24 gigawatt-hours).

33 *"Ionized" means the atom does not have an equal balance between its protons and electrons, and so is positively or negatively charged.*

34 *The three types of radiation are alpha, beta and gamma. They are discussed in more detail in section 6.2.*

35 *The exception is two very long-lived fission products, the isotopes Iodine -129 (I-129) and Technetium-99 (Tc-99). Because they decay very slowly this means that they emit radioactivity at a slow rate and, hence are very mild sources of radiation.*

So recycling and fissioning the heavy metals can accelerate the process of breaking down their radioactivity, leaving a much smaller volume of shorter-term waste products to deal with. Fuel recycling in the form of Mixed Oxide (MOX) fuel is currently being performed in France and Japan. Reprocessing facilities have been established in France and the United Kingdom, and a facility is about to be brought into service in Japan. The nuclear fuel cycle based upon MOX fuel recycling is shown in Figure 9.

FIGURE 9 : NUCLEAR FUEL CYCLE WITH RECYCLING

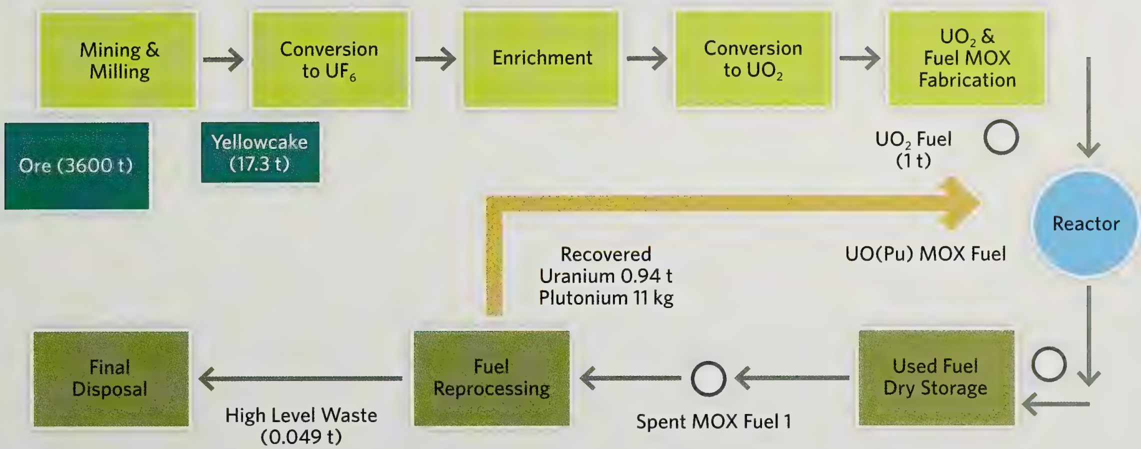



Figure 9 demonstrates that fuel reprocessing and reuse significantly reduces the amount of waste for which final disposal will be required, to 0.115 cubic meters of waste fuel from the original 3600 tonnes of uranium ore.

FIGURE 10 : TIMEFRAME FOR DECAY OF NUCLEAR WASTE

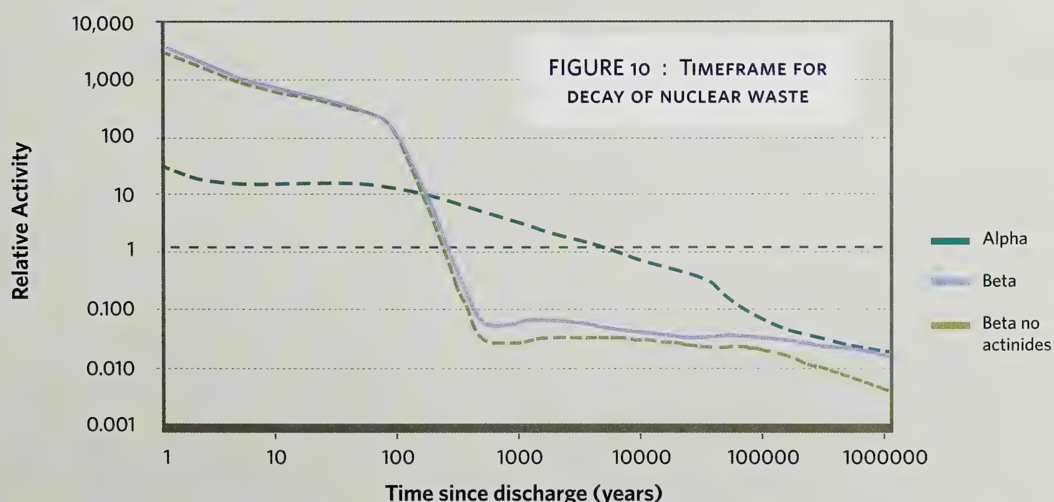



Figure 10 shows the time frame over which various important radiation particles (alpha and beta particles) emitted by used nuclear fuel are reduced. For reference, the horizontal dashed line shows the average radioactivity levels of alpha and beta activity found in nature in the earth's crust. Gamma radiation[36] reduces proportionally with the beta particle decays. It is primarily a source of heat, which is already reduced to low levels during the initial period in the spent fuel water pools and air cooled dry storage structures.

36 *The three types of radiation (alpha, beta, gamma) are discussed more fully in Chapter 6 (nuclear safety).*

### 5.4.1 Fuel disposal

In Canada the Nuclear Waste Management Organization (NWMO) was tasked with recommending to the Federal Government an approach to managing Canada's used nuclear fuel. Their recommended approach, which has been accepted, is Phased Adaptive Management.

The Phased Adaptive Management approach was developed following an extensive public consultation process. Its key elements are to provide safe, monitored storage of used fuel and the flexibility for future generations to make their own decisions regarding fuel management as technological advances are made. The approach involves three phases, during which options will be continuously evaluated:

1. In phase one, dry storage of used fuel at generating station sites will continue as currently practiced, while the option is assessed of a centralized shallow underground facility where used fuel could be stored on an interim basis and from which it could be retrieved. During this first phase, which will extend over approximately 30 years, work will be carried out on site selection for the centralized interim storage, as well as an environmental assessment, licensing and construction.
2. In the second phase, to be conducted over an additional 30 years, used fuel may be transferred to the centralized repository. Meanwhile, research and design will be carried out on a deep repository for permanent storage.
3. In the third phase, (after approximately 60 years) used fuel would be transferred to the deep geological repository for permanent storage. Depending on technology developments, in particular for fuel recycling, used fuel could be retrieved for reprocessing and recycling and only the waste fission products buried. Alternatively, if fuel recycling is not chosen, the used fuel could be prepared for burial in the deep geological repository while still retaining the option to retrieve it later.

The amount of waste material to be disposed will likely be significantly reduced through deployment of recycling technologies which are currently under research and development. As mentioned previously, the true waste fission products decay much more rapidly than the heavy metal actinides that are potentially recyclable as fuel.

### 5.4.2 Security

The nuclear proliferation issue concerns the possibility that nations will surreptitiously develop technology and facilities that allow the development of material for nuclear weapons. This can involve the enrichment of uranium to very high levels of purity – material referred to as Highly Enriched Uranium – or reprocessing spent fuel to remove plutonium-239. However, reprocessing/recycling reactor fuel does not produce weapons-grade plutonium, since power reactor fuel contains different isotopes of plutonium that reduce its effectiveness for explosions.

Currently, the main means of limiting the proliferation of weapons-grade material are the international safeguarding of nuclear materials by the International Atomic Energy Agency (IAEA) and development of new technologies. Used fuel is stored either in water pools or in dry storage structures made of high-strength reinforced concrete. These structures provide high levels of protection against possible hostile actions aimed at disrupting safe storage of the used fuel. Modern safety analysis evaluates the capability of these structures to withstand hostile attacks from a wide range of threats. In addition special seals are used by the IAEA to establish safeguarded facilities in conjunction with random inspections to verify that there has been no tampering with stored used fuel.

# 6 Nuclear safety

## 6.1 Overview

The issue of public safety inevitably arises in any discussion of nuclear power. Concerns relate to the possible impacts on public health and the environment due to the release of radioactive material from a nuclear power plant. Opinions on nuclear safety tend to be highly polarized between supporters and opponents, making it more difficult to develop an objective, balanced view of the risks and impacts.

This chapter outlines:

- Background for discussing radiation's impacts on health and the environment, including the comparison of natural and man-made sources.
- An overview of safety goals and approaches related to nuclear power plants.
- How nuclear plant design addresses safety functions.
- An overview of nuclear incidents throughout the history of this technology, their impacts and the lessons learned from them.
- The safety issues associated with low-level waste. (High-level waste management was discussed in chapter 5.)

Nuclear power has been used to generate electricity in North America, Europe and Asia for more than 50 years. During that time, there has only been one incident in which fatalities resulted from exposure to radiation. This was the Chernobyl accident in the former Soviet Union, which was the result of significant design and management deficiencies, as discussed later in this chapter. Otherwise, there have been no fatalities or severe health impacts caused by radiation exposure from a nuclear power plant.

The chapter focuses on safety issues specific to radioactivity. Nuclear power plants, like any thermal generating power plants, must manage safety issues related to high pressures and temperatures. But these hazards are not part of the scope of this discussion.

## 6.2 Radioactivity

Radioactivity is simply the release of energy from an unstable element. This energy may be released in a number of different forms. The three primary forms are:

- *Alpha particles (ionized nuclei of the helium atom).* These particles deliver energy over very short distances and can be easily shielded by such things as a sheet of paper or a garment (cloth or plastic).
- *Beta particles (charged electrons).* They penetrate further than alpha particles but deliver less intense energy. Beta particles can be shielded against by material such as a sheet of plywood.
- *Gamma rays (electromagnetic radiation similar in nature to X-rays).* They are significantly more penetrating than alpha and beta particles and can be shielded against by thick concrete walls, slabs of lead or a deep pool of water.

All living objects – human, animal and plant – are continuously exposed to radiation from natural sources and periodically from man-made sources. Natural sources include cosmic radiation that enters the earth's atmosphere from outer space, radiation from elements found in nature that are of primeval origin, and elements that are part of the food we eat. This radiation exposure is referred to as *background radiation.*

Other sources of *man-made radiation* exposure we experience come from dental and medical examinations and medical diagnostic and therapeutic treatments. These include X-rays, CT scans and treatments. As part of health and dental care, we are periodically subjected to radiation for diagnostic purposes (such as X-rays, CT scans, medical radioisotope diagnostics, etc.) or for therapeutic purposes (such as Cobalt-60 to treat cancer or Iodine-131 to treat a diseased thyroid gland).

The average annual radiation exposure (or *radiation dose*) that individuals receive worldwide (from both natural and man-made sources) is 2.8 milli-Sieverts[37] (mSv). The average exposure of individuals in Canada is approximately 3.4 mSv. Figure 11 shows the components of the average world-wide radiation dose.

Most of this exposure – 2.4 mSv on average – comes from natural sources. However, levels of natural radiation vary from location to location around the world, with a typical range of between 1 and 10 mSv, and there are locations where it is extremely high because of natural materials such as radium or pitchblende (which contains uranium). For example, in Ramsar, Iran the peak annual background level from terrestrial sources is 260 mSv, while in Kerala, India it is 35 mSv. At a popular beach in Brazil, the level is approximately 35 mSv. These levels are between 73 and 540 times the average dose to individuals world-wide. However epidemiological studies have not identified any negative health impacts in these communities.

Background radiation also depends on the state of economic development in the country we live in, and it varies with both our lifestyle and the voluntary choices we make. For example, a return flight across the country will lead to an additional effective dose of 0.08 to 0.1 mSv from cosmic radiation. Obviously, increased radiation exposure is voluntarily accepted by air-crews and by frequent fliers, although many in the latter group are unaware of their increased exposure because there is no perceptible impact on their health. Air crews on the other hand are subject to regulated limits on their exposure that impose a limit on their flying time during a year. Similarly, living at elevations close to sea-level will produce a lower dose of 0.27 mSv/yr from cosmic radiation while living at higher altitudes, such as 1600 m above sea-level gives a dose of 0.5 mSv/yr.

World-wide, the average annual radiation dose to individuals from nuclear power plants is approximately 0.0002 mSv/year. This is approximately 400 to 500 times less than the radiation dose from one transatlantic return air flight. It is also 12,000 times less than the average world-wide annual radiation dose individuals receive from natural background radiation sources.

If nuclear power is compared with coal generation, the maximum dose to an individual living next to a nuclear power plant for one year is approximately 0.02 mSv/yr., whereas the maximum radiation dose to a person living next to a coal plant for one year is approximately 0.2 mSv/yr. The increased dose from the natural radioactivity in coal is 10 times higher than that from living next to a nuclear power plant for the same period of time.

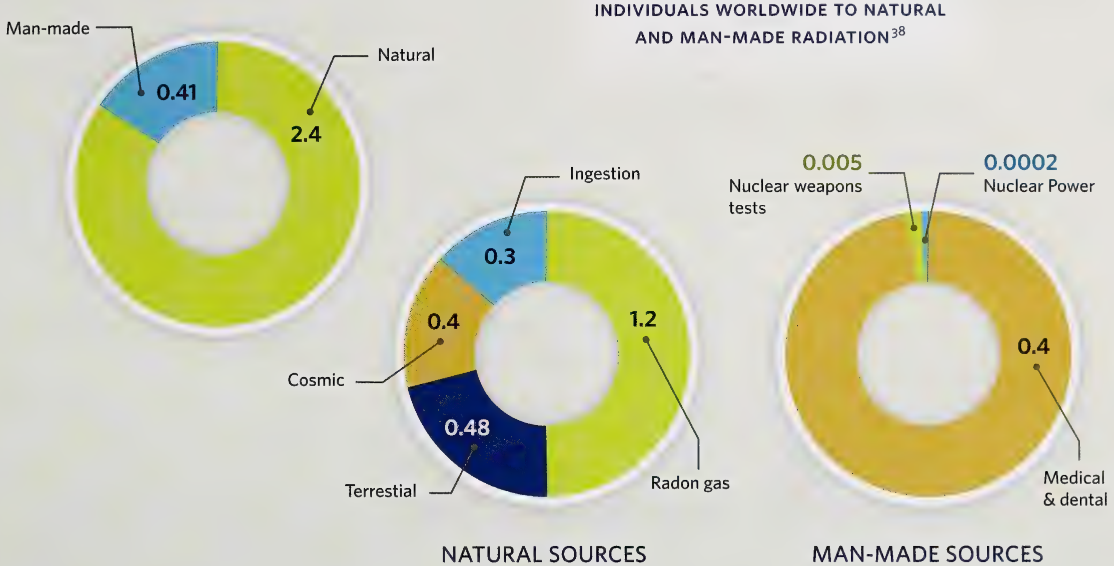
This raises the question of what levels of radiation dose have identifiable impacts on health. The majority of hard data has been accumulated from acute exposures of individuals and groups of individuals – i.e., people who have received relatively large doses over short time intervals. These data have been subject to detailed analysis by many experts and radiological protection organizations, including the International Committee for Radiological Protection (ICRP). Table 5 shows the levels of acute whole-body dose at which specific effects are perceptible in humans.

As the table indicates, the levels of acute dose that cause perceptible changes in human health are hundreds to thousands times larger than the doses people receive from natural sources. They are also orders of magnitude larger than the doses to persons living in the vicinity of nuclear power plants. At the low dose levels associated with natural sources and nuclear power, the effects are considered to be stochastic (random) and are expressed in terms of risks of additional cancers. Based upon various data sources, such as atomic bomb survivors, the ability to unambiguously distinguish increased risk becomes difficult at doses below approximately 200 mSv.

Significant controversy exists regarding health risks at the very low dose levels. Some groups claim a linear projection of risk downward with dose while others claim a beneficial effect for low dosages, based upon anecdotal observations. It is unlikely that this controversy will be resolved in the near future. At best, empirical evidence supports the conclusion that many other risks in daily life are far greater than those associated with low levels of radiation dose.

37 *The Sievert (Sv) is a unit used to quantify the effective energy transferred to biological tissue and a milli-Sievert (mSv) is one thousandth of a Sievert.*

FIGURE 11 : Average exposure of individuals worldwide to natural and man-made radiation[38]




Average annual radiation dose to individuals world-wide [mSv/year]

| Total Radiation Dose | |
|---|---|
| Natural | 2.4 |
| Man-made | 0.41 |
| **TOTAL** | **2.8** |

| Natural Radiation Sources | |
|---|---|
| Cosmic | 0.4 |
| Terrestial | 0.48 |
| Radon gas | 1.2 |
| Ingestion | 0.3 |
| **TOTAL** | **2.4** |

| Man-made Sources | |
|---|---|
| Medical & dental | 0.4 |
| Nuclear weapons tests | 0.005 |
| Nuclear power | 0.0002 |
| **TOTAL** | **0.4** |

TABLE 5 : Acute whole body dose and associated responses

| DOSE [mSv] | Effects on humans |
|---|---|
| 4500 to 5500 | Lethal dose: 99% of those exposed will succumb within 60 days of exposure |
| 3000 to 3500 | Lethal dose: 50% of those exposed will succumb within 60 days of exposure |
| 1000 to 2000 | Nausea and vomiting and hematological (blood) changes. Recovery very likely especially for healthy individuals. |
| 500 to 1000 | Mild effects only in first day of exposure with slight depression of blood counts |
| 250 to 500 | Minimal dose detectable by changes in white cell count |

38 *Source: United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR), "Sources and Effects of Ionizing Radiation", Report to the United Nations General Assembly, June 2000.*

## 6.3 Approaches to nuclear safety

A range of approaches ensure nuclear power plants are designed and operated so that the risk to public health and possible deleterious impacts on the environment are both minimized and maintained below legally regulated levels.

Safety principles affect all stages in the life cycle of a nuclear power plant, including design, construction, commissioning, operation, decommissioning and long-term storage of radioactive materials. At all stages, the national nuclear regulator of a country with civilian nuclear facilities is responsible for granting licenses to operate facilities and ensuring that regulatory requirements are being met through ongoing monitoring and assessment of licensee performance. (See chapter 8 for more on nuclear regulation).

One important principle is that all activities must be performed in a transparent manner and are subject to external scrutiny. One means of implementing this principle is the 1994 Convention on Nuclear Safety[39] coordinated by the International Atomic Energy Agency (IAEA), which is legally binding on all states that are signatories to the convention. Under this Convention meetings are held every three years for peer review of technical and management aspects of nuclear safety, with the aim of enhancing the level of nuclear safety on a global scale.

### 6.3.1 Safety goals

Safety goals are both 'qualitative' and 'quantitative.' A qualitative safety goal involves placing a limit on the societal risks posed by nuclear power plant operation. For this purpose, the following two qualitative safety goals have been established by the IAEA:

- Individual members of the public shall be provided a level of protection from the consequences of nuclear power plant operation such that there is no significant additional risk to the life and health of individuals; and
- Societal risks to life and health from nuclear power plant operation shall be comparable to or less than the risks of generating electricity by viable competing technologies, and should not be a significant addition to other societal risks.

Quantitative safety goals have the same intent as the qualitative ones, but are more targeted towards specific risks associated with certain situations and activities[40].

### 6.3.2 Defence-in-depth

The defence-in-depth approach to nuclear safety applies to all organizational, behavioural, and design activities that are safety-related. It ensures that overlapping provisions will detect and compensate/correct accidents or incidents. Defence-in-depth requires that all levels of defence be available while the plant is in operation; some systems may be relaxed when the plant is in non-operational modes.

This five-level scheme was developed by the International Atomic Energy Agency (IAEA).

1. Level 1 prevents deviations from normal operation and prevents failures of systems, structures, and components (SSCs).
2. Level 2 detects and responds to deviations from normal operational states, to prevent SSC failures from escalating to accident conditions and to return the plant to a state of normal operation.
3. Level 3 minimizes the consequences of accidents by providing adequate safety features, fail-safe design, additional equipment, and procedures. This includes safety features capable of leading the plant first to a controlled state and then to a safe shutdown state, and maintaining at least one barrier to prevent the release of radioactive material.
4. Level 4 controls severe plant conditions, prevents accidents from progressing to more severe consequences, and mitigates the consequences of severe accidents to ensure that radioactive releases are kept as low as reasonably achievable.

39 *The Convention on Nuclear Safety was adopted in Vienna on 17 June 1994. The Convention was drawn up during a series of expert level meetings from 1992 to 1994 and was the result of considerable work by Governments, national nuclear safety authorities and the Agency's Secretariat. Its aim is to legally commit participating States operating land-based nuclear power plants to maintain a high level of safety by setting international benchmarks to which States would subscribe. As of 04 April 2007, there were 65 signatories to the Convention and 60 contracting parties. All countries with operating nuclear power plants are now parties to the Convention.*

40 *Mathematically: Risk = Frequency of occurrence of an event x Consequence of the event.*

To achieve this objective the plant design must provide adequate protection of the containment barrier. This protection may be achieved by a robust containment design, by provisions to remove heat from containment and by procedures to prevent accident progression and facilitate accident management.

5. Level 5 will mitigate consequences of potential releases of radioactive materials that may result from accident conditions. This requires providing an adequately equipped emergency support centre, and plans for on-site and off-site emergency response capability.

## 6.4 Safety in nuclear power plant design

The primary focus of design is assuring that the plant has good safety features incorporated in various systems to either prevent or mitigate accidents for safe operation over the life of the facility. One very important factor is to constantly learn from the past and make changes in either design or operational procedures that improve safety.

Three basic safety functions are incorporated into nuclear power plants to either prevent or mitigate radioactive fission products being released during upset or accident events. These functions are Control, Cool and Contain, often referred to as the **3 Cs**. They provide the underlying technical principles for assuring nuclear safety in design and operation of a nuclear plant.

The 3 Cs maintain the integrity of inherent physical barriers incorporated into nuclear power plants that prevent or limit the release of radioactivity. The physical barriers in commercial nuclear power plants consist of:

1. A ceramic uranium dioxide fuel pellet which retains the majority of radioactive elements created from fission within the grains of the ceramic material. The fission products trapped in the fuel can be released only if the ceramic material overheats significantly for extended periods of time.

2. A metal cladding that surrounds the ceramic fuel pellets and is welded closed to form a leak-tight container for any radioactivity released from the fuel pellets. Again radioactivity can be released only if this barrier fails.

3. The piping system around the metal-clad fuel, through which a coolant flows to remove heat from the nuclear fuel. This piping acts as a barrier limiting the release of radioactivity into the reactor containment.

4. The reactor containment, which is a large, strong concrete structure (steel-lined in modern plants). This prevents release of radioactivity outside of the plant should the other three physical barriers fail.

### 6.4.1 Control

The primary design objective of the control safety function is to ensure that the first two barriers to radioactivity release – the fuel ceramic pellet and the metal cladding – do not fail.

In a nuclear reactor, the rate of energy production (power) is governed by the balance between how quickly neutrons are being produced and how quickly they are being absorbed by non-fissioning material. This balance is controlled by adjusting the amount of neutron-absorbing material in the reactor, in the form of rods of neutron-absorbing material inserted into the core. Changes in the number of neutrons produced in the reactor occur relatively slowly, making control of the reactor power a relatively easy function.

Should the balance between production and removal of neutrons become greater than desired, separate 'reactor shutdown systems' act independently of the power control systems. They are designed to rapidly reduce the reactor power to very low power levels. Equally importantly, the safety shutdown systems are designed to be 'fail-safe.' For example, if the electrical power supply should fail, gravity automatically causes the neutron-absorbing rods to drop into the reactor, thereby shutting it down.

Nuclear power plants cannot explode like an atomic bomb. This is a direct consequence of the manner in which fissile material is arranged in a nuclear reactor and the physics of fission chain reactions. It is physically impossible to generate the extremely rapid large fission chain reaction characteristic of a nuclear explosion without the reaction being terminated by inherent physical changes within the reactor.

### 6.4.2 Cool

Heat generated by fission is constantly transported away by a coolant fluid. After a nuclear reactor is shut down, energy continues to be produced at a low level (typically at a few percent of full power or less, depending upon the time since reactor shutdown). This residual 'decay heat' must be removed from the fuel by a coolant and transported to a heat sink (such as a steam generator or some other heat exchanger).

The cooling safety function includes systems designed for normal operation at either high or low power and also systems designed to provide reliable alternate means of removing heat from the reactor. One such safety system is the Emergency Core Cooling System, which provides an independent highly reliable supply of coolant to the reactor should an event like a rupture in piping cause a loss of normal coolant.

### 6.4.3 Contain

With very few exceptions, all commercial nuclear power plants in the world incorporate a containment structure as part of the design. Certainly all power reactors in North and South America, Europe and Asia have containments.

Containment is typically a large reinforced concrete structure surrounding the reactor which is designed to accommodate the discharge of steam from a ruptured pipe and limit the release of radioactive material outside the plant to safe levels. (These safe levels are prescribed by regulatory limits on the maximum permissible radiation dose to individuals living in the vicinity of the nuclear power plant. See Chapter 8 for information on regulating the nuclear industry.) Many new designs have a steel lining inside the concrete structure, while other designs have double-walled concrete structures.

### 6.4.4 External events

Nuclear power plants are designed not only to provide high levels of safety from events and accidents that occur within the plant itself, but also to ensure safe operation following challenges from external events.

An external event could be some natural phenomenon with the potential to cause damage, such as tornados, hurricanes, earthquakes and flooding, or some deliberate hostile act committed by persons or groups from outside the plant. These latter events, which have become of increased importance since the September 11, 2001 attacks in the U.S., are generally termed security events. Specific measures have been taken world-wide to address these security threats. For obvious national security reasons the nature of specific measures are not publicly available; however, as a result of them, nuclear power plants are not attractive targets for hostile actions.

Nuclear power plants are designed to be very robust against naturally occurring external events. This is achieved by a variety of means, such as the physical separation of important groups of safety functions to prevent simultaneous damage. Another example is designing special supports for systems so that they can withstand seismic events (i.e. earthquakes). Historical evidence from events such as hurricanes in the Gulf of Mexico, tornados in the Midwestern USA and Bruce County in Ontario, and earthquakes in Japan and other parts of the world have demonstrated the robustness of nuclear power plants.

## 6.5 Lessons from Past Nuclear Accidents

Over the past 56 years, a number of accidents have occurred in nuclear reactors, some of which have resulted in some off-site release of radioactive material. Several of these accidents involved research or non-commercial reactors during the early stage of nuclear power development and provided important lessons that contributed to increased safety in the later reactor designs. The more important accidents are discussed briefly below and the important lessons learned are identified.

### 6.5.1 NRX, Chalk River Ontario

In 1952 an accident involving an uncontrolled power increase occurred in the National Research Experimental reactor (NRX) at Chalk River, Ontario. The reactor core was badly damaged and had to be removed in a clean-up activity that is best known for the involvement of future U.S. president Jimmy Carter, who was a nuclear engineer in the U.S. navy at the time. The core was replaced and the reactor was subsequently restarted. No off-site radioactivity release occurred.

An investigation of the accident (Lewis, 1954) concluded that lack of separation between the control and shutdown functions was a major contributor to the accident. This led to the requirement in Canada that these two functions be totally separate and that shutdown be provided by an independent fast-acting system. Subsequently, in CANDU reactor designs that followed the Pickering A design, this requirement was extended by requiring that two totally independent, equally capable fast-acting shutdown systems be provided.

### 6.5.2 SL-1 Accident, Idaho, USA

The Stationary Low Power Reactor Number One (commonly referred to as SL-1) was a small military test reactor. In 1961 during a maintenance outage technicians were manually moving control rods when they inadvertently withdrew a rod more than they should have. This caused a rapid power excursion, melting of some of the fuel and a resultant energetic interaction between the molten fuel and the water coolant. The control rods were also ejected from the vessel and three operators were killed. Although there was no containment or confinement structure around the reactor other than an industrial-grade metal shed, the off-site radiological consequences were minor.

Although SL-1 was a military test reactor with little resemblance to commercial nuclear power reactors a number of lessons were learned from the accident. First, the importance was recognized of designing control rods such that removal of individual rods can only induce relatively small slow power increases. Second, small reactors where manual rod movement is allowed must provide automatic safety shutdown as a backup. Third, the presence of water in a reactor limits the release of the radiologically significant isotope Iodine-131, which dissolves in water.

### 6.5.3 Three Mile Island Unit 2, Pennsylvania, USA

This accident in 1979 occurred a few months after the startup of the second Pressurized Water Reactor unit at the Three Mile Island nuclear power station (TMI-2). The accident involved a major loss of cooling function for a sustained period of time. It was the first major accident in a commercial nuclear power plant. To this day it remains one of the most notorious nuclear accidents because of the media attention that occurred during the accident. Despite the fact that a significant portion of the core melted, the off-site consequences were insignificant and the maximum off-site dose to any member of the public was very much below levels that could cause health effects. The major consequence was a significant economic impact on the plant owner from the loss of the unit.

A number of major lessons were learned from the TMI-2 accident including:

- the importance of containment in limiting the release of radioactive material;
- the need for timely communication about operating experiences throughout the industry, to evaluate possible implications of events and ensure similar events do not lead to accidents;
- the need for systematic operator training including the use of full-scale simulators, similar to those employed in the air transportation industry;
- the need for emergency response organizations and clear communication during abnormal events and accidents; and
- the need to better understand accidents which cause severe damage to reactor cores with the related development of Severe Accident Management Guidelines to assist operators in mitigating such events.

One important outcome was the establishment of the Institute for Nuclear Power Operations (INPO), an organization whose role is to coordinate and promote safe operation and practices, improve information sharing, and provide for industry benchmarking among North American utilities.

### 6.5.4 Chernobyl Unit 4, Ukraine

On April 26, 1986 the worst commercial nuclear power reactor accident in history occurred in the Fourth Unit of the Chernobyl Nuclear Power Station in Ukraine, which at that time was part of the Soviet Union. A large uncontrolled power increase occurred in the reactor during a safety system test. This destroyed the reactor and a large quantity of radioactive material was ejected to the environment during the initial stage of the accident. For the next five days the graphite moderator in the reactor core continued to burn, resulting in an ongoing release of radioactivity to the environment. The main contributor to the accident's severity was the lack of fast-acting shutdown systems, while the main contributor to the large release was the lack of any containment structure around the reactor. Other factors involved included poor safety culture, poor design and poor communication between designers and operators.

In responding to the accident a large number of station operating staff and firefighters were exposed to very high doses of radiation and over a period of a number of months 28 of these individuals died from the effects of radiation exposure. The population in the nearby town of Pripyat was evacuated and permanently relocated. The radiation plume spread around Europe causing great concern. Subsequently the reactor was encased in a concrete vault where it remains awaiting final cleanup and decommissioning.

A large epidemiological study was initiated and continues to this day with reports at ten-year intervals following the accident. Theses studies are conducted by the Chernobyl Forum[41], led by the International Atomic Energy Agency and the World Health Organization and involve many other agencies of the United Nations.

One conclusion of the Chernobyl Forum studies is that the consequences of the Chernobyl accident are often overstated.[42] They estimate that the total number of individuals that could eventually die from radiation exposure from this accident to be about 4000 out of an exposed population of 600,000. The detailed studies have identified a total of 56 persons in this exposed population whose deaths in the past twenty years following the accident can be attributed to the effects of radiation released from the accident.[42] This number includes 28 individuals who died within four months in 1986 as a result of high exposures received in responding to the event, 19 subsequent deaths between 1986 and 2004 of persons involved in responding to the consequences of the accident and 9 individuals who died of thyroid cancer.

National responses to the Chernobyl accident varied substantially between the different countries in the region. Poland, for example, immediately instituted emergency protection measures to distribute potassium iodide (KI) tablets to the population. This compound protects the thyroid gland of individuals exposed to Iodine-131, a radioisotope with a half-life of 12 days, and is particularly important for young children who are vulnerable to the exposure. In Belarus, Russia and Ukraine (which were part of the Soviet Union at the time), no similar early widespread protective actions were taken outside of the areas close to the reactor,

41 *The members of the Chernobyl Forum include the International Atomic Energy Agency (IAEA), World Health Organization (WHO), United Nations Development Programme (UNDP), Food and Agricultural Organization (FAO), United Nations Environment Programme (UNEP), United Nations Office for the Coordination of Humanitarian Affairs (UN-OCHA), and United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR).*

42 *The Chernobyl Forum, "Chernobyl's Legacy: Health, Environmental and Socio-Economic Impacts", International Atomic Energy Agency (IAEA), April 2006.*

such as the city of Pripyat. As a result, about 4000 individuals in these three countries who were children at the time of the accident have since developed thyroid cancer. Fortunately, since the form of thyroid cancer is very treatable, only 9 of these individuals have died and the survivors have favorable prognosis. Had potassium iodide tablets been more widely distributed these thyroid cancers most likely could have been avoided.

The background radiation levels at this time in the areas around Chernobyl, including Pripyat, are approximately two times the natural background radiation level that existed in the area prior to the accident.

As a result of the intense international focus on nuclear safety following the Chernobyl accident the World Association of Nuclear Operators (WANO) was formed, with headquarters in London, UK. This organization provides similar functions to INPO for cooperatively promoting safe operations and information exchange amongst nuclear operators world-wide.

## 6.6 Managing low-level waste

The safe disposal of waste nuclear fuel is discussed in chapter 5. However, there are other kinds of waste products that must be handled safely:

- Low-level waste includes minimally radioactive materials from normal operation, such as used protective clothing and cleaning materials (mops, paper towels).
- Intermediate-level waste includes activated components that have been replaced during routine maintenance, and resins and filters and materials left after a plant has been decommissioned.

Low-level waste, which represents approximately 95% of the total non-fuel waste volume, is handled through volume reduction processes including either incineration or compaction. The reduced volume is then stored on-site in above-ground concrete structures. Intermediate level waste is more radioactive than low level waste and not subject to volume reduction processes. However, it makes up a much smaller volume. Intermediate-level waste is stored in steel-lined concrete containers set into the ground.

In Ontario, storage of low- and intermediate-level waste is centralized at Ontario Power Generation's Western Waste Management Facility (WWMF) located at the Bruce Nuclear Power Development site. In 2002, the Municipality of Kincardine approached Ontario Power Generation, requesting that the company consider a long-term storage facility for low and intermediate waste. Following a study, the Municipality endorsed an option to develop a Deep Geological Repository which is undergoing environmental assessment and licensing processes. Separate vaults for low level and intermediate waste storage will be constructed at depths around 660 m below the surface.

# 7 Nuclear electricity in Alberta

## 7.1 Overview

This chapter looks at some implications of integrating a base-load nuclear generating plant in Alberta, including:

- Issues related to the Alberta transmission grid
- Regional and provincial impacts associated with communities, infrastructure needs and the economy.

In many respects a large base-load nuclear plant is much like a large base-load coal-fired plant (with respect to integration in the grid and regional impacts) or to other large industrial projects (with respect to socioeconomic impacts).

## 7.2 Nuclear plants and the Alberta Transmission System

The transmission grid is the 'highway' over which electrical energy travels, connecting supply and demand, and electrical generation plants must be integrated safely and reliably into the transmission grid. This integration function involves planning and coordination, even in a jurisdiction such as Alberta with a competitive supply market.

The Alberta Electric System Operator (AESO) is an independent, not-for profit entity responsible for planning and operating Alberta's grid. The AESO's mandate states that it must ensure that transmission capacity exists to accommodate generation and load (demand) as it arrives on the system. Achieving this mandate is challenging because:

1. The AESO must plan the transmission system, including expansion, to meet the requirements of a competitive and decentralized generation sector.
2. There is often a mismatch between the construction lead times required for generation and transmission projects. Typically, it takes five to eight years to build a major transmission line (including the work to define and select routes, obtain approvals, acquire new rights-of-way and construct the line and substation facilities). A new gas-fired or renewable-energy generating unit takes less time than this, so the AESO's transmission planning must anticipate load growth and generation development to have facilities in place when and where they are needed.

A nuclear plant requires a longer construction time, so it may actually be easier for the AESO to ensure that adequate transmission facilities are available

A nuclear plant does not affect the cost of transmission differently from any other plant of similar size. Like any other new generator, owners of a nuclear plant would pay for the costs of interconnecting their facility to the grid. Adding a large new generator, nuclear or not, may require significant reinforcement of the regional transmission system or even of the bulk transmission system, depending on the exact location, size and type of the generator. These costs are allocated across all network users.

However, the size of nuclear units *could* create some operating issues. For example, in any electric system, the size of the largest unit affects the amount of reserve capacity needed in case the unit becomes unavailable. In Alberta, the largest units are currently 450-MW coal units. (Typical coal plants consist of two or more such units.) Adding a nuclear unit of 800 MW could require increased operating reserves or, alternatively, additional transmission interconnections with neighbouring jurisdictions. According to Alberta's market rules, any such impact on system operations or transmission interconnections would not be charged to the account of the new generator but would be allocated across all users.

## 7.3 Infrastructure and resources required for a nuclear plant

Construction of a nuclear power plant in Alberta would involve a wide range of activities and resources. Many of the resources, such as engineering expertise, skilled labour and steel, to name only a few, have been constrained in Alberta's current economic environment due to the level of economic activity in recent years.

A selected site would require infrastructure including a power supply; access to technological, community, and service support; earthquake, meteorological and hydrological monitoring; working space for project management activities; and living accommodations for workers if the site is remotely located. Weather is not a particular concern since nuclear plants currently operate in northern latitudes such as Finland.

A significant siting consideration would be the availability of a sufficient quantity of cooling water. Another consideration is that access needs to accommodate the transportation of large reactor components by road, rail, or barge.

The manufacture and sourcing of components and materials for a nuclear project requires a great deal of advance planning and project management, much like many of Alberta's large and complex energy and industrial projects. Some components would be manufactured in Alberta, some elsewhere in Canada, while some would be imported. The Canadian Energy Research Institute estimates that about 7.5% of the cost of building a CANDU-6 reactor, for example, would be for the purchase of imported items.[43]

## 7.4 Socioeconomic impact of a nuclear plant

A nuclear plant, with its long construction period, capital-intensity, and need for skilled labour during both construction and operation, would have significant socioeconomic impacts on the province and particularly on the region in which it was located. In general, the impacts would be similar to those of any of the large energy industrial projects currently underway in Alberta.

### 7.4.1 Labour impacts

The construction and subsequent operation of a nuclear plant would create new jobs in three different ways:

- *Direct employment:* labour employed to construct and then operate the plant,
- *Indirect employment:* jobs created in other sectors as a result of initial expenditures on plant construction and operation, and
- *Induced employment:* jobs created as a result of new expenditures in other sectors that come about because of higher total labour income.

This allocation is somewhat arbitrary – it is often a matter of judgment whether particular types of construction or manufacturing employment are direct or indirect. However, as a rule of thumb, the Idaho National Laboratory[44] calculates that for every direct job created through nuclear power plant construction or operations, approximately four jobs are either induced by the plant or indirectly tied to the plant.

#### CONSTRUCTION PHASE

The number of jobs created during construction depends on the size and scale of the plant being built. The private-sector proponent for a large (4000-MW) nuclear project in the Athabasca-Grande Prairie-Peace River area estimates that the total of direct, indirect, and induced labour needs for a 10-year construction phase would be 84,000 person-years[45]. Of this, 28% would be direct employment, 5% indirect, and 67% induced.

A different study by the U.S. Department of Energy[46] assessed the construction requirements for a smaller Generation III plant (approximately 1300 MW), and found that its construction would require in excess of 1.3 million person-hours (nearly 700 person-years) for pipefitters alone. Peak construction requirements of a project of this size would exceed 10% of the Alberta workforce in trades such as ironworking, boilermaking and pipefitting.

These construction requirements, however, are for plants that would be very large additions to the Alberta system. For purposes of this report, the panel has

43 CERI, 2008

44 DOE 2004

45 Golder/SJ Research, 2008

46 DOE 2005

generally considered a smaller 800-MW base-load plant, which would lead to a correspondingly smaller workforce.

## OPERATING PHASE

The operational staffing level of a nuclear power reactor is well-established. The Nuclear Energy Institute (NEI) reports that the average nuclear plant in the U.S. creates 400–700 direct full-time positions for a 1000-MW nuclear plant, and about the same number of induced positions[47] in the local economy. Another study (in support of the U.S. Nuclear Power 2010 Program) collected best-estimate data for the next-generation plants beginning to come online, and estimated that the requirements would be in excess of 700 employees per reactor.

The Canadian Energy Research Institute (CERI) has undertaken a similar assessment of the 17 CANDU reactors operating in Canada. The direct workforce employed at the reactors is 16,137, or 949 per reactor, which is somewhat higher than is expected for the advanced CANDU reactors.[48]

A nuclear plant in Alberta with a somewhat smaller capacity[49] would have lower labour requirements. However the comparison is not simply linear, since many jobs such as training, security, and health physics technicians do not depend on plant size.

For comparison, a typical coal-fired plant (with two 450-MW) units employs a significantly smaller number – 100-200 direct employees (excluding mine operations), depending on the age of the plant and technology used.

Specialists from outside Alberta may be required for some of the most highly skilled jobs in a nuclear plant, such as nuclear engineers and health physicists to ensure the radiation health and safety of workers and the public. It might be desirable to develop the nuclear-specific skill sets within Alberta, both for future employment within Alberta as the sector grows and as a technical-service export to a growing international nuclear sector. This would require training programs to help develop the necessary expertise, which could be sponsored by government or facility owners.

TABLE 6 : Estimates of fiscal impacts (MILLIONS OF $)

| Source of Estimate | GDP | Labour Income | Taxes | | |
|---|---|---|---|---|---|
| | | | Federal | Provincial | Local |
| **Construction** | | | | | |
| Bruce Power (4000-MW plant) | 12,648 | 5,542 | 222 | 160 | 27 |
| **Operations** | | | | | |
| Bruce Power (4000-MW plant) | 1,111 | 523 | 81 | 86 | 18 |
| NEI (2008) (1000-MW plant) | 430 | 40 | 75 | 20 | |
| CERI (average CANDU unit ≈750 MW) | 370 | | | | |

The estimated tax effects of the Bruce Power plant were calculated by Alberta Finance using an input-output simulation.

47 NEI, 2008

48 Timilsina, 2008

49 *For purposes of this report, a nuclear plant of 800 MW has been assumed, as approximately the same size as a two-unit coal-fired plant (the most comparable addition to the Alberta grid). No current nuclear reactor design is of exactly this size.*

### 7.4.2 Economic impact

Like any large industrial project, a nuclear plant will add to the province's GDP, as well as contributing to tax revenues and labour income. Table 6 summarizes the impacts of various nuclear additions, according to information from a variety of sources, including the proponents of a 4000-MW unit in Alberta, the Nuclear Energy Institute (NEI) in the U.S., and CERI.

The NEI's calculation was based on total direct expenditures (local, state-wide, and national) for an average 1000-MW nuclear plant in the U.S., along with a multiplier to estimate the total impact on GDP. Regionally, the NEI reports that every dollar of direct expenditure on a nuclear plant generates slightly more than a dollar of additional indirect spending in the local community[50]. This does not include revenues associated with the sale of electricity, which would be approximately US$400–500 million per year for a 1000-MW plant.

The CERI study concluded that the annual economic activity for all 17 CANDU reactors—again excluding the sale of electricity—amounts to C$6.3 billion per year, or C$370 million per reactor, which is close to the NEI figure of US$ 250–300 million per reactor.

## 7.5 Community issues: population growth and public services

Absorbing a nuclear plant, like any large industrial project, presents challenges as well as opportunities for the local community, particularly during the construction phase when several thousand workers may be added to a community for a relatively short time.

In 2006, the Government of Alberta examined issues raised by rural communities in light of the rapid expansion of the oil sands. The study found that high growth areas face special challenges because of issues such as:

- Provincial resource allocation formulas and three-year planning horizons do not account for current rates of population growth.
- There is insufficient coordination between provincial and municipal authorities.
- There is a mismatch between municipal responsibilities to provide infrastructure and their ability to raise revenue.

Gaps that were identified in high-growth-rate areas include:

- Shortages of housing, and affordable housing in particular.
- Difficulties in attracting additional public sector workers to handle short-term increases in population.
- An inability to expand infrastructure—particularly in water treatment, waste treatment, health services, and transportation—because capital expenditures must be made before additional tax revenues from a development project are realized.

Without changes to Alberta's municipal funding programs, it is likely that a nuclear project would raise similar issues.

50 *NEI, 2008*

# 8 Nuclear regulation in Canada

## 8.1 Overview

In Canada nuclear regulation is solely a federal jurisdiction, and provinces have no regulatory responsibilities specific to nuclear generation. This chapter outlines the role of the Canadian Nuclear Safety Commission and the process involved in applying for permission to construct and operate a new nuclear power plant.

## 8.2 Canadian Nuclear Safety Commission

Historically, nuclear regulation was carried out by the Atomic Energy Control Board (AECB) which was established by the Atomic Energy Control Act of 1946. The current national nuclear regulatory agency, the Canadian Nuclear Safety Commission (CNSC), was established by the *Nuclear Safety and Control Act* (NSCA) of 2000. This Act is the cornerstone of the CNSC's regulatory framework.

The CNSC regulates the use of nuclear energy and materials to protect health, safety, security and the environment, and to respect Canada's international commitments on the peaceful use of nuclear energy. It is an independent quasi-judicial agency which reports to Parliament through the Minister of Natural Resources. The CNSC is composed of a Commission Tribunal and a staff organization.

The Commission Tribunal is a quasi-judicial tribunal and court of record, which is responsible for:

- making transparent decisions on the licensing of nuclear-related activities in Canada;
- establishing legally binding regulations;
- setting regulatory policy direction on matters relating to health, safety, security and environmental issues affecting the Canadian nuclear industry.

CNSC staff:

- review license applications;
- prepare regulations and regulatory documents (see below);
- enforce compliance with the NSCA, regulations, and any license conditions imposed by the Commission.

The CNSC issues regulatory documents to provide guidance to applicants (see Table 7). These documents are developed through a transparent consultative process involving licensees, government and non-governmental organizations, and the general public. These documents form the basis for the assessment of license applications.

Licenses granted by the Commission may contain conditions that must be met by licensees in addition to the requirements of legislation and associated regulations. Table 7 outlines the NSCA regulations and other Canadian legislation with which applicants for a nuclear plant license must comply.

The CNSC is currently updating its regulatory framework for licensing new nuclear power plants to reflect Canada's commitment to international standards and practices. The intention of the CNSC is to align the regulatory framework with the International Atomic Energy Agency (IAEA) nuclear safety standards which set out high-level safety goals that apply to all reactor designs. This alignment will assure Canadians that any new nuclear power plants built in Canada meet the highest international standards for health, safety, security and environmental protection.

## 8.3 Process for licensing new nuclear power plants

The lifecycle of a nuclear power plant can be divided into five major phases, each of which requires a separate license. These phases are:

1. Site preparation
2. Construction

TABLE 7 : Regulation and legislation affecting nuclear plants

| CNSC regulations | Other federal legislation* |
|---|---|
| *General Nuclear Safety and Control* | *Nuclear Liability Act* |
| *Radiation Protection* | *Nuclear Fuel Waste Management Act* |
| *Class I Nuclear Facilities* | *Canadian Environmental Assessment Act* |
| *Nuclear Substances and Radiation Devices* | *Canadian Environmental Protection Act 1999* |
| *Packaging and Transport of Nuclear Substances* | *Fisheries Act* |
| *Nuclear Non-Proliferation Import and Export Control* | *Species at Risk Act* |
| *Nuclear Security Regulations* | *Migratory Bird Convention Act* |
| | *Canada Water Act* |

| CNSC Regulatory documents |
|---|
| RD-310 – Safety Analysis of Nuclear Power Plants (*February 2008*) |
| RD-337 – Design of New Nuclear Power Plants (*November 2008*) |
| RD-346 – Site Evaluation for New Nuclear Power Plants (*November 2008*) |
| RD-360 - Life Extension of Nuclear Power Plants (*February 2008*) |
| RD-204 - Certification of Persons Working at Power Plants (*February 2008*) |

* This list is not exhaustive; other federal legislation may apply.

3. Operation
4. Decommissioning, and
5. Abandonment

### 8.3.1 Environmental Assessment

A prerequisite for licensing is that an Environmental Assessment must meet the requirements of the *Canadian Environmental Assessment Act* (CEAA). This assessment establishes whether a project may have significant impacts on the environment and whether they can be mitigated. The environmental assessment for a nuclear project is carried out by the CNSC, but costs are paid for by the proponent.

The process is initiated when a proponent applies under the NSCA for a license to prepare a site. Additionally, the proponent must submit a complete project description, which is used by Federal departments and agencies to determine if any associated regulatory decisions are required. This process is facilitated through the Major Projects Management Office, created by the Government of Canada to coordinate the necessary licensing and regulatory activities applicable to large projects.

The site-preparation application requires that the proponent provide the Project Description, an Environmental Impact Statement (EIS), information on decommissioning plans and financial guarantees that sufficient funds will be available for decommissioning at any subsequent licensing stage.

The environmental assessment for a new nuclear plant considers all phases in the lifecycle of a nuclear power plant and may be conducted as either a comprehensive study or by a review panel. Comprehensive studies must be conducted for large, complex projects that may have significant negative environmental impacts or which attract public interest and concern. The CNSC or the Federal Minister of the Environment can refer an application for a review by an Environmental Assessment panel, which provides a structured and focused review with public input. Members of a review panel are appointed by the Federal Minister of the Environment.

While nuclear regulation is solely and entirely a federal jurisdiction, the CEAA makes provision for the Minister of Environment to enter into agreements with provincial and territorial governments where both governments have

interests in an environmental assessment. This harmonization, through the appointment of a Joint Review Panel, is intended to avoid unnecessary overlap of assessment activities at two levels of government. Opportunities exist for participation and input from the public and other stakeholders throughout the environmental assessment process.

In such cases, the Joint Review Panel submits a report to the Minister of the Environment who makes the report publicly available. The Governor in Council considers the report and approves a Government Response which includes a recommendation on whether the CNSC can issue the *Licence to Prepare Site* for a new nuclear power plant.

### 8.3.2 Construction License Application

The application for a *Licence to Construct* requires the applicant to demonstrate that the proposed design of a nuclear power plant will meet regulatory requirements and that the plant can be safely operated on the approved site for the duration of its life. The information supplied by the applicant includes (but is not limited to) such items as:

- a description of the proposed design that takes into consideration site-specific physical and environmental characteristics;
- baseline environmental data for the site and surrounding areas;
- a Preliminary Safety Analysis Report (PSAR) that demonstrates design adequacy in meeting regulatory safety requirements;
- information on potential releases of nuclear substances and other hazardous materials together with proposed measures to control releases;
- measures to mitigate effects on the environment and health and safety of persons that may arise from construction, operation and decommissioning the facility; and
- programs and schedules for recruiting and training operations and maintenance staff.

### 8.3.3 Operating License Application

The application for a Licence to Operate requires that the applicant demonstrate to the CNSC that it has established safety management systems, plans and programs that will ensure safe and secure operation of the facility. This information includes but is not limited to such items as:

- description of structures, systems and equipment at the nuclear power plant;
- the design and operating conditions of the structures, systems and equipment;
- a Final Safety Analysis Report that demonstrates that safety requirements are met;
- methods, measures, policies and procedures for commissioning systems and equipments, operating and maintaining the facility, handling nuclear substances and hazardous materials and controlling their release to the environment, nuclear security and emergency preparedness activities.

### 8.3.4 Decommissioning

At the end of a nuclear plant's useful life it is decommissioned and over a period of time the site will be returned to "greenfield" conditions. A license from the CNSC to perform this decommissioning work is required. Information on decommissioning plans and financial guarantees for funding decommissioning must be provided at all stages of licensing to provide assurance that all necessary activities can be completed.

For example, Ontario Power Generation (OPG) is responsible for the decommissioning and nuclear waste management associated with all nuclear stations in Ontario. The CNSC has approved financial guarantees totaling $9.999 billion related to these plants. Every year contributions are made to segregated accounts to fund future decommissioning and waste management activities and, as of the end of 2006, OPG had accumulated $7.5 billion for these purposes.

### 8.3.5 Licensing Timeframe

The regulatory process for licensing a new power plant, starting from the initial site application to commercial operation, requires that the applicant receive three separate licenses: one to prepare the

site, the second to construct the plant and the third to operate the plant. The Nuclear Safety Control Act does not contain provisions for combined licenses for these three phases, as is the case in some international jurisdictions. However, applications to prepare a site, construct and operate the plant can be assessed in parallel. Since the CNSC conducts these licensing activities on a cost-recovery basis, the financial risk associated with parallel license assessments is borne by the applicants.

The CNSC has estimated that the approximate duration of licensing activities from receipt of an application for *License to Prepare Site* to *License to Operate* is approximately nine years, as shown in the table below. This estimate, based upon past experience takes into account some overlap in environmental assessment, licensing and applicant activities. The estimate is also contingent upon the CNSC having adequate resources to perform its reviews in a timely manner.

TABLE 8 : Estimated timeframe for nuclear power plant licensing

| Activity | Duration |
|---|---|
| Aboriginal consultation | Ongoing |
| Environmental assessment and license to prepare site | ~ 36 months |
| Site preparation | ~ 18 months |
| License to construct | ~ 30 months (minimum 6-month overlap with the previous activities) |
| License to operate | ~ 24 months |
| Applicant's activities (e.g., plant construction) | ~ 48-54 months |
| Total duration | ~ 9 years |

FIGURE 12 : Process for obtaining a license to construct or operate a new nuclear power plant in Canada

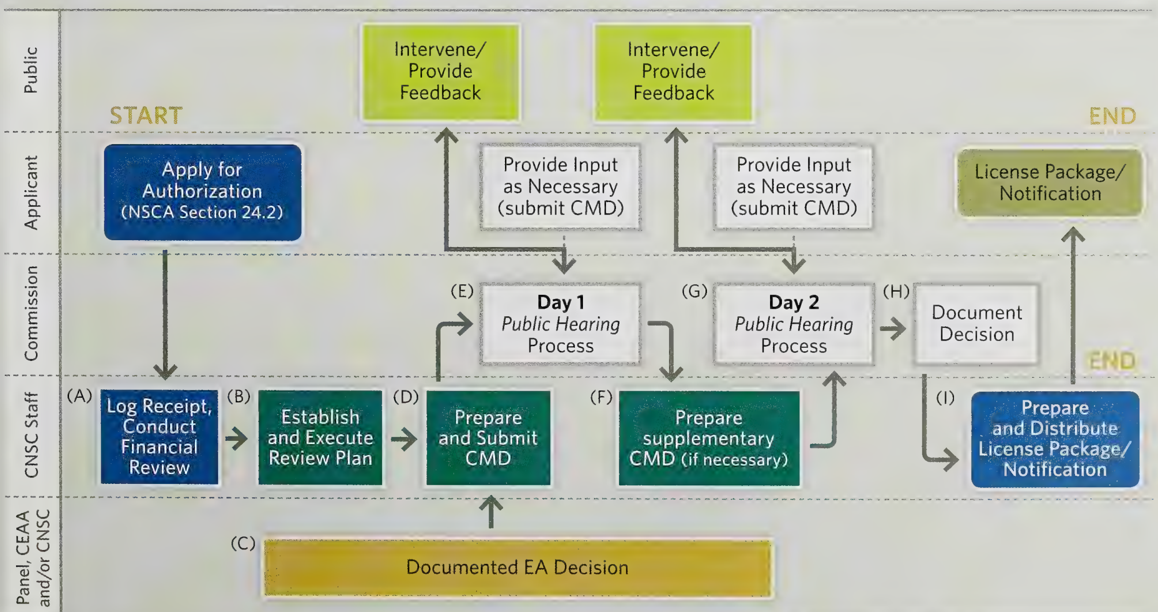



Figure 12 outlines the process for obtaining a license to construct or operate a new nuclear power plant. Source: CNSC (2008). CMD stands for 'Commission Member Document' (these are documents provided to the Commission (CNSC) members containing information and recommendations for approval.

# 9 Conclusion

A proposal by private-sector investors to build a nuclear facility in Alberta would likely lead to an active public discussion and debate. Such a debate would be most productive if it were conducted with a clear understanding of the nature of nuclear power generation, and its relative risks/benefits compared with alternatives. This report is based on current scientific information to help provide such an understanding.

In preparing this report the panel makes the fundamental assumption that Alberta's economy and population will continue to grow and that additional electrical power will be needed to maintain and improve the standard of living of Albertans. The evidence to support this assumption is shown in Chapter 2. Chapter 3 discusses the alternative means available to maintain a match of supply and demand for electricity and the associated cost of electricity and environmental impacts of each alternative. Options include more fossil-fuel-burning power plants, more renewable sources and greater energy efficiency, as well as nuclear power.

While the focus of this report is on nuclear power generation, the panel deliberately did not take a position as to whether nuclear power is the only or the preferred means to meet any electricity supply-demand gap. There are attractive opportunities for Alberta to expand electricity generation through fossil fuel, renewable and nuclear generation technologies, and each technology has trade-offs associated with it.

We have attempted to elucidate, in a plain-language non-technical manner, the nuclear power plant technology that is available and/or is in use in various parts of the world and the issues that are associated with nuclear power.

## 9.1 Technical

The technology of nuclear power has evolved significantly over the past decades. New designs, based on learning from previous incidents and from long-term safe operation, are safer, and are being used world-wide. In comparison with the nuclear power plants first deployed some fifty years ago, the nuclear plants currently being developed are safer, more efficient and easier to control and operate. Within the industry, these newer designs are referred to as Generation III reactors and reflect improved engineering design, improved materials and the much better control systems made possible by modern technology. Canada, along with every other country with operating nuclear power plants, is a signatory to The Convention on Nuclear Safety, committed to maintaining the highest level of safety.

Nuclear power plants in Canada have triple redundancy with respect to safety. First, the design and controls provide for inherently safe operation. Second, should an accident or failure occur, there are fail-safe mechanisms to rapidly cool the reactor core. Third, the entire reactor system is encased to prevent leakage of radioactive material.

## 9.2 Environmental

Nuclear power does not release carbon dioxide. This is a significant difference (in environmental terms) between it and technologies using traditional coal and natural gas. Compared with hydroelectric and wind power, nuclear has a smaller physical footprint on the landscape.

The offsetting concern is related to plant operation and nuclear waste disposal. While the spent fuel removed from a reactor is radioactive, more than 99% of this material is made up of the heavy metals uranium and plutonium, which can be recycled into nuclear fuel. The remaining waste fission products decay comparatively quickly. Thus a program of separating the spent fuel and recycling heavy metals will dramatically reduce the amount of waste to be dealt with and the time period during which this material would be radioactive at levels above the natural background radiation.

If fossil fuel generation is fitted with carbon capture technology to eliminate carbon dioxide emissions, $CO_2$ also presents concerns regarding long-term storage.

## 9.3 Regulation/jurisdiction

In Canada, the Federal Government has the authority and responsibility for approving and regulating all nuclear facilities and nuclear-related activities. This raises the question of whether this authority is sufficient to allow the construction of *any* new nuclear facility. Presumably, if there were a specific and important national interest at stake, nuclear facilities could be constructed solely on the authority of the Federal Government. It is doubtful that a nuclear power plant would fall into this category.

Therefore in the case of a nuclear power plant for the generation of electricity or for the production of process steam, the normal provincial approvals that are required for any major project would also be required. These required approvals flow from the Province's constitutional responsibility for land and resources and cover the broad range of issues related to land use. Hence, in addition to federal approval, any nuclear power facility would also have to comply with provincial regulations. However, if a project did meet provincial regulations fully, it is doubtful it could be prevented from going ahead simply because it was a nuclear facility.

## 9.4 Other social issues

Among other items, the panel was asked to consider a process to respond to social issues. It is the panel's view that there are no separate social issues which fall within provincial jurisdiction that are uniquely associated with nuclear power generation plants. Any project of the magnitude under consideration will have social impacts in areas such as schools, hospitals, transportation infrastructure, aboriginal communities, the local economy, housing and so on. Significant though these issues might be, they are regularly dealt with by the Government of Alberta and its agencies and affected municipalities. As such, the panel feels it has neither the information nor the expertise to offer advice which the Government of Alberta does not already have.

The panel recognizes that there may be issues other than those featured in this report which could have a bearing upon any decision to approve a large nuclear plant. Resolution of these types of issues involves public policy and economics, as well as science and technology. As is the case in most areas of government responsibility, it can be a challenge to find the most appropriate consensus among competing interests. It is usually the case that finding the most timely and best resolution is aided if discussed within the context of current and scientifically factual information. It is the panel's hope and expectation that this report will be a helpful contribution to a public discussion on nuclear power generation based on scientific evidence and empirical findings from experiences with nuclear power generation around the world.

# Appendix A: Panel Mandate

**Government of Alberta**
**Department of Energy**
**Ministerial Order 31/2008**

I, MEL KNIGHT, Minister of Energy, pursuant to section 7 of the Government Organization Act, make the Order in the attached appendix, being the Nuclear Power Expert Panel Order.

Dated the fifth day of May, 2008

Original signed by
Mel Knight, Minister of Energy.

## Schedule A: Duties and functions of the panel

- The Panel shall prepare a balanced and objective Report for the Government of Alberta on factual issues pertinent to the use of nuclear power to supply electricity in Alberta.
- The Report shall be submitted to the Minister of Energy
- The Panel will identify in its Report the relevant facts underlying the following issues:
  - » Alberta's projected future demand for electricity;
  - » Nuclear Power Generation Technologies;
  - » Comparison of nuclear with other base load generation technologies;
  - » Integration of nuclear power into the supply of electricity in Alberta;
  - » Current and Future Nuclear Power Generation - Canada, World;
  - » Risk and Benefit Assessment - Environment, Health and Safety, Cost
  - » Waste Management and Liability;
  - » Social Issues; and
  - » Process to Respond to Social Issues.

## Panel members

### Honourable Dr. Harvie Andre, BSc, MSc, PhD, FEIC, PC. (Chair)

Dr. Andre is a chemical engineer, who after receiving his doctorate from the University of Alberta in 1966, became one of the founding professors of Chemical Engineering at the newly established University of Calgary, where in addition to helping to establish the full four year undergraduate program, he supervised several postgraduate students doing research in process dynamics, control and optimization.

From 1972 to 1993, Dr. Andre was a Member of Parliament and from 1984 to 1993 was a cabinet minister in the Government of Canada. Subsequent to retiring from Parliament he has been involved primarily in the oil and gas industry. He is and has been on the board of several private and public companies and currently is President & CEO of a company that designs, manufactures, leases and sells drilling tools used in the petroleum industry.

### Dr. Joseph Doucet, B.Mgt.Sc., MSc, PhD.

Dr. Doucet holds the Enbridge Professorship in Energy Policy in the University of Alberta's School of Business. In the School of Business he directs a specialized MBA program in natural resources, energy and the environment as well as the Center for applied business research in energy and the environment (CABREE). Dr Doucet is also the Director of the University of Alberta's School of Energy and the Environment (SEE).

His professional interests are in energy and regulatory economics and policy and he is a frequent commentator and analyst of energy market and policy issues in the media. He regularly provides policy advice and analysis to government departments, regulatory agencies and private sector entities in the energy sector. He is also active in academic and professional associations and is currently the President of the Canadian affiliate of the International Association for Energy Economics (IAEE). Dr. Doucet's research has appeared in journals such as *The Energy Journal, Energy Economics,* the *Journal of Regulatory Economics* and the *Canadian Journal of Economics*. He is a member of the Editorial Board of the *Journal of Regulatory Economics,* and between 2000 and 2006 he was Editor of the journal *Energy Studies Review.*

Dr. Doucet received his MSc and PhD in Operations Research from the University of California, Berkeley, after taking his Bachelor's degree in management science (Summa Cum Laude) from the University of Ottawa. Prior to joining the University of Alberta in 2000 Dr. Doucet was on the faculty of Université Laval. He has also been a visiting faculty member at the University of Florida and Université Montpellier in France.

### Dr. John Luxat, BSc, MSc, PhD

Dr. Luxat is a Professor in the Department of Engineering Physics at McMaster University where he holds the NSERC/UNENE Industrial Research Chair in Nuclear Safety Analysis. He teaches nuclear engineering and nuclear safety to graduate and undergraduate students and conducts research in nuclear safety, nuclear reactor physics and nuclear fuel cycles.

Prior to joining McMaster University in 2004, he had 32 years experience working in many areas of nuclear safety and nuclear engineering in the Canadian nuclear industry, most recently as Vice President, Technical Methods at Nuclear Safety Solutions Limited and, prior to that, as Manager of Nuclear Safety Technology at Ontario Power Generation. He has represented Canada on many international projects and has advised international organizations such as the International Atomic Energy Agency (IAEA) and the Nuclear Energy Agency of the Organization for Economic Development (OECD). He has consulted to numerous Canadian companies on nuclear safety and nuclear engineering issues and provided advice to government organizations at the national and provincial level.

He is a member of the Board of Atomic Energy of Canada Limited, the Advisory Board of the International Association for Structural Mechanics in Reactor Technology, the Canadian Nuclear Society and the American Nuclear Society. He served as the 2005/06 President of the Canadian Nuclear Society and was the Treasurer of the Society.

In 2004 he was awarded the Canadian Nuclear Society/Canadian Nuclear Association Outstanding Contribution Award for his significant contributions to safety analysis and licensing of CANDU reactors. He has authored more than 140 conference and journal papers and numerous technical reports on nuclear safety issues and has been invited to lecture at academic and technical institutions around the world.

Dr. Luxat obtained his BSc and MSc degrees in Electrical Engineering from the University of Cape Town, South Africa in 1967 and 1969, respectively. In 1972 he obtained his PhD degree in Electrical Engineering from the University of Windsor, Ontario.

### Dr. Harrie Vredenburg, BA, MBA, PhD, ICD.D

Dr. Vredenburg is Professor of Strategy at the University of Calgary's Haskayne School of Business where he holds the Suncor Energy Chair in Competitive Strategy and Sustainable Development, a research chair affiliated with the University's Institute for Sustainable Energy, Environment and Economy (ISEEE). He teaches in MBA, MSc, Executive MBA, and PhD programs as well as in executive development and directors' education programs. He is also Adjunct Professor of Environmental Science in the Faculty of Environmental Design.

He served for 10 years as founding Academic Chair of the University's MSc program in sustainable energy development and for 13 years as founding Director of IRIS, the Haskayne School's International Resource Industries and Sustainability Studies Centre. He has authored or co-authored more than 50 research articles, book chapters and case studies on business strategy, energy, environment and sustainable development in journals such as *Organization Science, Journal of Applied Behavioral Science, Ecology & Society, American Journal of Public Health, Strategic Management Journal, Journal of Business Ethics, Harvard Business Review, MIT Sloan Management Review and Journal of Petroleum Technology.*

He has served as a member of the Alberta Environmental Appeals Board, a member of the board of directors of the Pembina Institute, a member of a federal expert panel advising the Minister of Health on tobacco industry regulation, and a member of a specialist group advisory board of the International Union for the Conservation of Nature. He currently serves on the board of directors of Petrobank Energy, a public company, and the Van Horne Institute for International Transportation and Regulatory Affairs. Prior to joining the University of Calgary he was a professor at McGill University in Montreal. Dr. Vredenburg earned a PhD in strategic management from the University of Western Ontario, an MBA in international business and finance from McMaster University and an honours BA in history from the University of Toronto. He earned the ICD.D designation of the Institute of Corporate Directors as a certified corporate director.

# Appendix B: Glossary of terms

| | |
|---|---|
| **Actinides** | A series of 15 elements starting at actinium (atomic number 89), ending at lawrencium (atomic number 103) and including uranium (atomic number 92) and plutonium (atomic number 94) with large, heavy nuclei made up of large numbers of protons and neutrons. They are unstable elements that decay by emitting radioactivity. |
| **Atomic number** | The number of protons in the nucleus of an element. The atomic number distinguishes the chemical properties of the element. |
| **AECB** | Atomic Energy Control Board, the former Canadian federal nuclear regulator (now replaced by the CNSC). |
| **AECL** | Atomic Energy of Canada Limited, the Crown Corporation that designs and sells CANDU reactors. |
| **AESO** | Alberta Electric System Operator, responsible for planning and operating Alberta's transmission system. |
| **Alpha particles** | Nuclei of the helium atom (i.e., two protons and two neutrons bound together). |
| **ARC** | Alberta Research Council. |
| **Beta particles** | High-energy, high-speed electrons. |
| **BWR** | Boiling Water Reactor, a design that uses a single coolant loop in which water reaches boiling temperature to produce steam. |
| **CANDU** | Canada deuterium uranium, a reactor design based on natural uranium fuel with heavy water (deuterium) as a moderator. |
| **Capacity factor** | The percentage of time that a generating unit is available to produce energy. |
| **CERI** | Canadian Energy Research Institute. |
| **CNS** | Canadian Nuclear Society. |
| **CNSC** | Canadian Nuclear Safety Commission, the federal nuclear regulator. |
| **$CO_2$** | Carbon dioxide. |
| **Depleted uranium** | Uranium from which U-235 has been removed, usually as part of the process of making nuclear fuel. |
| **Deuterium** | An isotope of hydrogen that includes one proton and one neutron (compared with the more usual form of hydrogen that has no neutron.) |
| **EPRI** | Electric Power Research Institute. |
| **ERCB** | Energy Resources Conservation Board. |
| **Fission** | The splitting of a heavy atom into smaller fragments when it is hit by a neutron. |
| **Fission products** | Unstable isotopes of lighter elements created when the nucleus of a heavier element is split. |
| **Gamma radiation** | Electromagnetic radiation similar to X-rays. |
| **GDP** | Gross Domestic Product, a measure of total economic activity in a region or country. |
| **GW** | Gigawatt, one billion watts. |

| | |
|---|---|
| **GWh, GWd** | Gigawatt-hour and gigawatt-day, respectively. The energy equal to one gigawatt of generating capacity operating over one hour or one full day. |
| **Heavy water** | Water containing a higher-than-usual percentage of molecules made up of deuterium rather than typical hydrogen. |
| **IAEA** | International Atomic Energy Agency. |
| **IEA** | International Energy Agency. |
| **IGCC** | Integrated Gasification Combined Cycle, a technology for creating synthetic gas from coal or other sources and burning it to produce energy. |
| **INL** | Idaho National Laboratory. |
| **Life-cycle analysis** | Considers the environmental impacts of all the components throughout the life of a facility, from manufacturing equipment, through construction, installation, and operations to eventual decommissioning. |
| **LLRWMO** | Low-Level Radioactive Waste Management Office. |
| **$m^2$** | Square meters. |
| **$m^3$** | Cubic meters. |
| **MW** | Megawatts, a million watts. |
| **MWh** | Megawatt hours. |
| **Neutron** | A subatomic particle with no electric charge. The nucleus of any atom is made up of protons and neutrons. |
| **NEI** | US Nuclear Energy Institute. |
| **NGCC** | Natural gas combined cycle. |
| **NOx** | Nitrogen oxides. |
| **NWMO** | Nuclear Waste Management Organization, an organization created by the owners of used nuclear fuel to manage Canada's nuclear waste. |
| **person-years** | A person-year represents the amount of work done by one person employed for a full year. |
| **PBMR** | Pebble bed modular reactor. |
| **PWR** | Pressurized Water Reactor. |
| **PHWR** | Pressurized Heavy Water Reactor. |
| **RBMK** | *Reaktor bolshoy moshchnosti kanalniy* (a high-power channel-type reactor). |
| **SCO** | Synthetic crude oil. |
| **SO2** | Sulphur dioxide. |
| **Sievert** | A unit for expressing dosages of radiation. It reflects the biological effects of radiation received. A milli-Sievert is one one-thousandth of a Sievert. |
| **U-235** | Uranium-235, an isotope of uranium made up of 92 protons and 143 neutrons. It is naturally fissile and releases neutrons. |
| **U-238** | Uranium-238, the most common isotope of uranium, made up of 92 protons and 146 neutrons. |
| **V** | Volts. |
| **W** | Watts. |
| **WANO** | World Association of Nuclear Operators. |
| **Wh** | Watt hours. |
| **WNA** | World Nuclear Association. |

# Appendix C: Bibliography


| | |
|---|---|
| Abengoa, 2008 | Abengoa Solar (2008). *Concentrating Solar Power.* Web presentation. Retrieved August 2008 from http://www.iian.ibeam.com/events/penn001/26826 |
| ACR, 2004 | Alberta Chamber of Resources (2004). *Oil Sands Technology Roadmap: Unlocking the Potential.* |
| AECL, 2008 | Atomic Energy of Canada Limited (2008). *ACR-1000 Technical Summary.* Retrieved August 21, 2008 from http://www.aecl.ca/Reactors/ACR-1000.htm |
| AESO 2005 | Alberta Electric System Operator (2005). *20-Year Outlook Document* (2005–2024) [Electronic version] |
| AESO, 2007a | Alberta Electric System Operator (2007). *Future Demand and Energy Outlook (2007–2027)* [Electronic version]. |
| ARC/INL 2008 | Alberta Research Council and Idaho National Laboratory, *The Nuclear Energy Option in Alberta,* Oct. 2008 |
| AREVA, 2008 | AREVA (2008). *EPR: the first generation III+ reactor currently under construction.* Retrieved August 2008 from http://www.areva-np.com |
| AREVA, 2008a | AREVA (2008). ANTARES: *HTR for electricity/process heat generation* and *ANTARES – The AREVA HTR-VHTR Design.* Retrieved August 2008 from http://www.areva-np.com |
| ATMEA, 2008 | ATMEA (2008). *The mid-sized Generation III+ PWR you can rely on.* Website http://www.atmea-sas.com accessed August 2008. |
| AUA, 2007 | Australian Uranium Association, "Russia sets course for major nuclear expansion," *AUA Newsletter*, 4, July–August 2007, http://www.uic.com.au/news407.htm |
| Bryce, 2008 | Bryce, R. (2008). Nukes Get Small, *Energy Tribune,* Featured Stories July 16, 2008, Retrieved August 2008 from http://www.energytribune.com/articles.cfm?aid=948 |
| CERI, 2008 | Canadian Energy Research Institute (2008). *The Canadian Nuclear Industry: Contributions to the Canadian Economy,* Canadian Nuclear Association, Ottawa, Ontario. |
| Chernobyl, 2005 | The Chernobyl Forum (2005). *Chernobyl's Legacy: Health, Environmental and Socio-economic Impacts and Recommendations to the Governments of Belarus, the Russian Federation and Ukraine.* International Atomic Energy Agency. |
| Chicago, 2004 | University of Chicago (2004). *The Economic Future of Nuclear Power.* Retrieved from http://www.ne.doe.gov/np2010/reports/NuclIndustryStudy-Summary.pdf |
| Daniel, Doucet and Plourde | (2007). Daniel, T., J.A. Doucet and A. Plourde, "Electricity Industry Restructuring: The Alberta Experience", in *The Challenge of Electricity Restructuring* (Andrew N. Kleit, editor, published by Rowan and Littlefield) 2007. |
| DOE, 2004 | U.S. Department of Energy (2004). *Study of Construction Technologies and Schedules, O&M Staffing and Cost, Decommissioning Costs and Funding Requirements for Advanced Reactor Designs.* Prepared by Dominion Energy Inc., Bechtel Power Corporation, TLG, Inc., and MPR Associates, May 2004. |

DOE, 2005 — US Department of Energy (2005). DOE NP2010 *Nuclear Power Plant Construction Infrastructure Assessment.* MPR-2776, Rev. 0.

EIA, 2003 — Energy Information Administration (2003). *Official Energy Statistics from the U.S. Government - CANDU Reactors, data as of October 10, 2003.* Retrieved August 2008 from http://www.eia.doe.gov/cneaf/nuclear/page/nuc_reactors/china/candu.html

EIA, 2008 — Energy Information Administration (2008). *Official Energy Statistics from the U.S. Government—New Commercial Reactor Designs.* Retrieved August 2008 from http://www.eia.doe.gov/cneaf/nuclear/page/analysis/nucenviss2.html#_ftn12

ERCB, 2008 — Energy Resources Conservation Board (2008). *Alberta's Energy Reserves 2007 and Supply/ Demand Outlook 2008–2017 ST98-2008* [Electronic version].

GA, 2008 — General Atomics (2008). GT-MHR—*Inherently Safe Nuclear Power for the 21st Century.* Websites http://www.gt-mhr.ga.com and http://www.ga.com accessed August 2008.

GE, 2008 — General Electric (2008). *Advanced Boiling Water Reactor (ABWR) fact sheet* and ESBWR fact sheet. Retrieved August 2008 from http://www.gepower.com/prod_serv/products/nuclear_energy/en/index.htm

GenIV, 2007 — Generation IV International Forum (2007). *2007 Annual Report*. Printed by the OECD Nuclear Energy Agency for the Generation IV International Forum.

GOA, 2008 — Government of Alberta (2008). *Talk About Wind Power.* Retrieved August 2008 from www.energy.gov.ab.ca/Electricity/pdfs/FactSheet_Wind_Power.pdf

Golder/SJ, 2008 — Golder Associates and SJ Research Services (July, 2008) *Preliminary economic and financial impact analysis of a proposed nuclear power generation facility in the Peace Country of Northern Alberta.*

HPG, 2008 — Hyperion (2008), *Hyperion Power Generation.* Website http://www.hyperionpower generation.com/index.html accessed August 2008.

IEA, 2005 — International Energy Agency (2005). *Projected Costs of Generating Electricity 2005 Update.* International Energy Agency of the Organisation for Economic Co-operation and Development (OECD), 2005.

IEA, 2007 — International Energy Agency (2007). *Trends in Photovoaltaic Application Survey report of selected IEA countries between 1992 and 2006.* Report IEA-PVPS T1-16:2007.

IRIS, 2008 — IRIS Official Web Site (2008). *IRIS Project Overview.* Website http://hulk.cesnef.polimi.it accessed August 2008.

LaBar, 2002 — LaBar, M.P. (2002). *The Gas Turbine – Modular Helium Reactor: A Promising Option for Near Term Deployment.* General Atomics report GA-A23952. Retrieved August 2008 from http://gt-mhr.ga.com/images/ANS.pdf

Loughran & Kulick, 2004 — Loughran, David S. and Jonathan Kulick (2004): "Demand-Side Management and Energy Efficiency in the United States", *The Energy Journal,* Vol. 25, No. 1.

Majorowitcz, 2008 — Majorowitcz, J. & Moore, M. C (2008). *Enhanced Geothermal Systems (EGS) Potential in the Alberta Basin.* Retrieved August 2008 from http://www.aeri.ab.ca/sec/new_res/docs/Enhanced_Geothermal_Systems.pdf

MHI, 2008 — Mitsubishi Heavy Industries (2008). *Nuclear Energy Systems Headquarters.* Website http://www.mhi.co.jp/en/nuclear/index.html accessed August 2008.

NEI, 2008 — Nuclear Energy Institute (2008). *Key Issues—New Reactor Designs.* Retrieved August 2008 from http://www.nei.org/keyissues/newnuclearplants/newreactordesigns

News, 2008 — American Nuclear Society (2008. *Nuclear News, 10th Annual Reference Issue.* Vol. 51, No. 3.

| | |
|---|---|
| NuScale, 2008 | NuScale Power Inc. (2008) *NuScale Power.* Website http://www.nuscalepower.com/home.html accessed August 2008. |
| Ordorica, 2007 | Ordorica-Garcia, G., Croiset, E., Douglas, P. L., Elkamel, A., & Gupta, M. (2007). Modelling the energy demands and greenhouse gas emissions of the Canadian oil sands industry. *Energy Fuels 2007*, 21, 2098–2111. |
| OSU, 2008 | Oregon State University (2008), *Media Release–New Company,* reactor Design May Boost Nuclear Energy. Retrieved August 2008 from http://oregonstate.edu/dept/ncs/newsarch/2008/Jul08/nukes.html |
| PBMR, 2008 | Pebble Bed Modular Reactor (Pty) Limited (2008). *Future Energy.* Website http://www.pbmr.com, accessed August 2008. |
| PSIRU, 2005 | S. Thomas, *The Economics of Nuclear Power: Analysis of Recent Studies,* Public Research Services International Research Unit, University of Greenwich, UK, July 2005. |
| Torgerson, 2007 | Torgerson, D. (2007). AECL Looks to the Future With the ACR-1000. *Electricity Transmission and Distribution Today.* Vol. 19, no. 8, October 2007. Retrieved August 2008 from http://www.aecl.ca/Assets/Publications/ET-AECL.pdf |
| Timilsina, 2008 | Timilsina, G. et al. (June 2008). *The Canadian Nuclear Industry: Contributions to the Canadian Economy.* Canadian Energy Research Institute. |
| Westinghouse, 2002 | Westinghouse (2002). *AP600 Background.* Website http://www.ap600.com accessed August 2008. |
| Westinghouse, 2008 | Westinghouse (2008). *AP10000.* Website http://www.ap1000.com accessed August 2008. |
| WISE, 2008 | World Information Service on Energy Uranium Project (2008). *World Nuclear Fuel Facilities.* Website http://www.wise-uranium.org/efac.html accessed August 2008. |
| WNA, 2008 | World Nuclear Association (2008). *Information Papers—Advanced Nuclear Power Reactors.* Retrieved August 2008 from http://www.world-nuclear.org/info/inf08.html |
| WNA, 2008a | World Nuclear Association (2008). *Information Papers—Country Briefings, Nuclear Power in Japan.* Retrieved August 2008 from http//www.world-nuclear.org/info/inf79.html |
| WNA, 2008b | World Nuclear Association (2008). *Information Papers—Country Briefings, Nuclear Power in Russia.* Retrieved August 2008 from http://www.world-nuclear.org/info/inf45.html |
| WNA, 2008c | World Nuclear Association (2008). *Information Papers—Small Nuclear Power Reactors.* Retrieved August 2008 from http://www.world-nuclear.org/info/inf33.html |

ISBN 978-0-7785-6335-8